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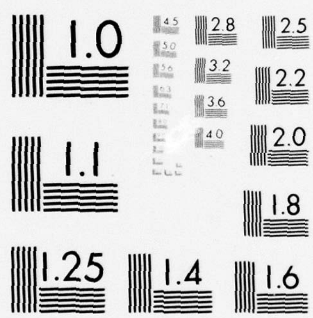

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Report No. FAA-RD-77-19

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AN INVESTIGATION OF THE LIGHTNING ELIMINATION AND STRIKE REDUCTION PROPERTIES OF DISSIPATION ARRAYS

Rodney B. Bent
Sigrid K. Llewellyn

DEPARTMENT OF TRANSPORTATION • UNITED STATES OF AMERICA •

Final Report

May 1976

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16. Abstract

The dissipation of thunderclouds to the point where lightning is inhibited has been a topic of conversation for over two hundred years.
The purpose of this study is to investigate the controversial concept of dissipation, using single and multiple points to permit the Federal Aviation Administration engineers to formulate a program for protection of navigation facilities.
This report discusses the historical background of the dissipation concept, along with the physical process related to cloud dissipation and a theoretical investigation of electrostatic field and corona around tower structures.
The investigation and measurements of single point and multiple point corona currents are discussed. The results of photographic recordings and magnetic link current measurements of lightning are presented. Previous data provided from facilities using the multiple point concept to eliminate lightning is correlated with a current analysis. Facilities provided for the investigation are NASA/GSFC MILA, NASA/GSFC Rosman and Eglin AFB.
Based on theoretical work, experimental tests and photographic data, the conclusions are that multiple points in a practical situation do not produce more corona current than a single point and that multiple points do not eliminate lightning and do not provide any more protection than a conventional lightning protection system.

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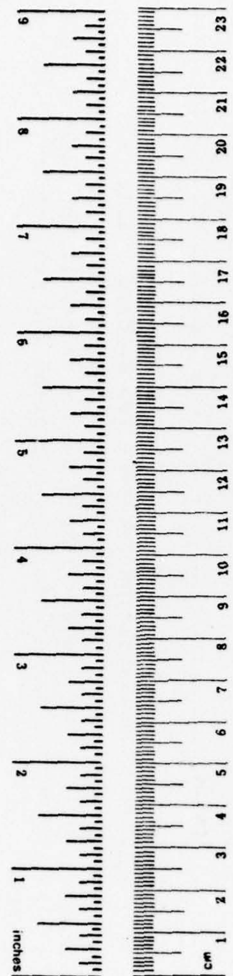
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

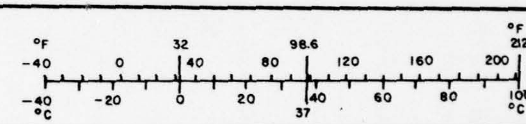
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



FOREWORD

This document was prepared by Atlantic Science Corporation of Indian Harbour Beach, Florida for the Department of Transportation, Federal Aviation Administration, Washington, D.C. under contract N00014-73-C-0348 from the Office of Naval Research (ONR).

The authors are particularly indebted to Mr. Ray Barkalow of the FAA who closely monitored the progress of the contract, and whose continued interest and technical suggestions contributed significantly to the success of the project. We wish also to acknowledge the appreciable contributions of Mr. J. Hughes of ONR whose interest and valuable suggestions in co-ordinating this work with that of other interested scientists throughout the United States, resulted in a thorough and complete study.

Mr. Jack Dowling, Site Director at the NASA/MILA satellite tracking station happily provided assistance in both technical and equipment areas. The authors are very appreciative of his considerable support which led to the successful completion of the corona current investigations. The capable and timely assistance of Mr. Marlin Forstrum, Eglin Air Force Base is greatly appreciated, as is the support and encouragement of Dr. Martin Uman of the University of Florida.

The contributions of Mr. W. Peele, Purdue University, Messrs. J. Jackson and E. Taylor of the NASA/Rosman satellite tracking facility, Chief Robbins of the USCG Loran site at Jupiter, Florida, Chief Warrant Officer Dieroef, USCG, Miami, Mr. W. Starnes of NASA/MILA, Mr. C. Malloy, U. S. Forestry Service, Messrs. G. Apostalakis and N. Mercado of the FAA, Atlantic City and Mr. C. Myers of Vitro are all greatly appreciated. Finally, but still with consideration and appreciation, we are very much indebted to the cheerful and expert typing of Jacqueline Walker.

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1.0 HISTORY OF THE DISSIPATION CONCEPT

It is a common misconception that lightning rods discharge clouds and thus prevent lightning. The rod only serves as a means to route the lightning harmlessly to ground by diverting the lightning when it approaches the striking distance at about 10 to 100 yards away. The lightning leader is "unaware" of any feature on the ground until it has come to within this striking distance. In the two hundred years since Benjamin Franklin investigated lightning many manufacturers have tried to influence the public in the dissipation principle of lightning protection or elimination. This technique most certainly does not work and the lightning physicists' thoughts on this subject are discussed in masterly fashion by Golde[1] in the following statement:

> "It is a manifestation of human weakness that a prejudice once acquired tends to be retained even in the face of overwhelming factual evidence contradicting the basis on which it was founded. In the realm of science a prejudice may be termed a misconception. Such a misconception which has persisted for over two hundred years and which is still widespread is the belief that a lightning conductor has the ability, or indeed the purpose, of dissipating silently the electric charge in a thundercloud thus preventing the "protected" building being struck".

The long history of the interest in the dissipation possibility started when Benjamin Franklin first put forth his idea on the lightning rod furnishing two alternative explanations of its action. He suggested that the rod would conduct the stroke to ground thus eliminating any damage, or that the rod might prevent lightning, this idea being derived from laboratory experiments of point discharge. In his publication in Poor Richard's Almanac in 1753 he definitely leaned toward the attraction principle. One of the first buildings equipped with a lightning rod was the bell tower of St. Mark's in Venice. It had been completely destroyed by lightning three times and severely damaged nine times in a period of about 400 years. In 1766 a lightning rod was installed and no further lightning damage has occurred since.

In 1930 a US patent was granted to J. M. Cage[2] of Los Angeles, California for a dissipation system claiming to protect areas and structures against lightning. In its main application of shielding petroleum storage tanks, wires armed with points were suspended from steel towers completely enclosing the area to be protected and aiming at the prevention of lightning discharges by dissipation.

Another application of the dissipation idea is found in the radioactive lightning rods, which supposedly utilize the excess ionization to help protect against lightning. Golde in his book on Lightning Protection[3] examined these claims. A response was made by the medical profession, by Roberts et. al. in 1966[4] who were worried about the use of the typical radioactive sources for therapeutic purposes, which exceeded the intensity of the radioactive rods by a factor of 5×10^6. When directed toward the roof of the hospital room, these sources would induce a very serious lightning hazard if the claims made for the much weaker radioactive rods were justified. But fortunately there is no evidence that therapeutic rooms in hospitals are struck more frequently than other structures in the same region! Cassie in 1969[5] further examined the effect of a radio therapeutic source theoretically and found that even for such an intense emitter the striking distance would only be reduced by 6 to 10 cm, which leaves the effect of the much weaker radioactive rod completely negligible.

A number of well known scientists have discussed the dissipation possibilities. The charging current in a thunderstorm has been measured in various ways to be of the order of one ampere. To prevent lightning by dissipating this charging current, according to Chalmers,[6] 50,000 points would be needed within the area of intense field below the cloud. This area is about 1 km^2 requiring the points to be located about 4.5 cm apart which is clearly impractical. These numbers are based on a maximum current of 20μA given off by a single point, and on excessive values of updraft, assuming erroneously that the corona discharge could reach the charge center of the cloud. Looking at the problem in terms of charge

transferred, Chalmers states that based on an average value of 30 coulombs brought to ground during a lightning flash, it would take a single point about 2 1/2 weeks to neutralize this charge. In an average storm the lightning flashes occur at intervals of minutes, so again the order of 50,000 points would be needed.

Golde[1] looks at this problem in a similar fashion. Considering average electric fields of 200 V/cm under a thundercloud, an average charge of 30 coulombs being dissipated by a lightning flash, and a flash rate of two per minute, it follows that 6,000 conductors each 50 feet high and spaced over 1/2 square mile would be required to prevent one lightning flash.

Extremely high point-discharge currents have been measured at the top of the tower on Mount San Salvatore in Switzerland. On occasion currents of up to 4 mA were recorded on this tower of effective height in excess of 2500 ft lasting for the order of one half hour depending on the speed of the thundercloud. But in the words of Berger[7] who monitored this data, a single strong lightning stroke can transport more charge than the point-discharge current of a tall tower during an entire summer.

Evidence of the point- discharge can be seen in the form of St. Elmo's Fire, in particular in high mountains where thunderclouds frequently develop only slightly above the peaks creating intense electric fields. While this phenomenon is indicative of a highly charged atmosphere, the currents actually flowing might not be that extreme. According to Chapman[8] 10μA of corona current can be seen as a glow under the right circumstances, and 100μA are easily visible.

It has been argued that adding more points to the lightning conductors would increase greatly the amount of corona current given off. Chalmers[6] quotes about eight experimenters who have investigated single point versus multiple point corona currents. In general it is found that in the laboratory multiple points will give off more corona current than a single point, however under the actual conditions in the

field the results are the other way around and more corona current is obtained from a single point. This discrepancy is due to the relative distances between cloud and ground and the points, which cannot be properly simulated in the laboratory between capacitor plates and test points.

2.0 THE PHYSICAL PROCESS RELATED TO CLOUD DISSIPATION

Figure 1 shows a typical thunderstorm cell in the early stages of development. At that time the cloud has reached a height of only 28,000 feet and the general flow of air under the cloud is upward . In order to investigate whether the corona discharge released at the ground will pass into the main charge region of the cloud, we can assume a typical vertical

25 min →

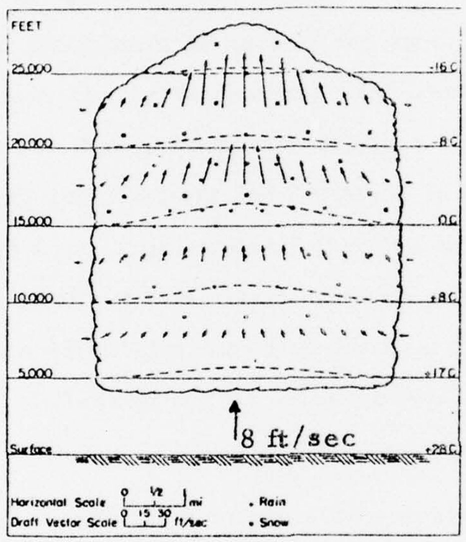


Fig. 1 A thunderstorm cell in the early stages of development. (From U.S. Dept of Commerce Weather Bureau Report, June 1949).

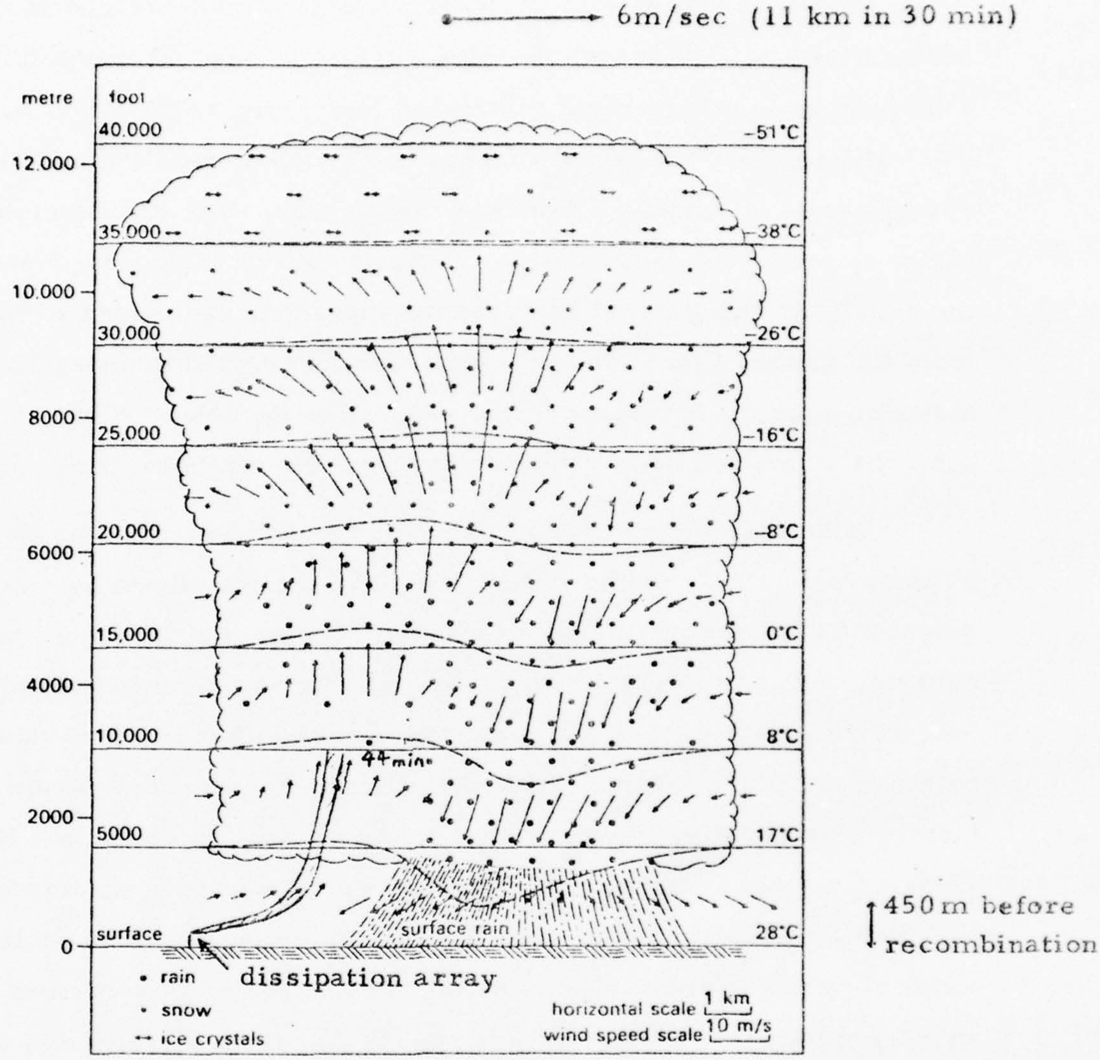
motion due to updraft of an uncharged particle to be no more than 8 feet/ sec. This uncharged particle will take approximately 25 minutes to attain an altitude of 12,000 feet, should the cloud remain stationary during this time. The ions are, however, charged and will also proceed upward under the influence of the ambient electric field. Assuming the mobility of small ions at 1.5×10^{-4} m/sec per V/m and a pre-thundercloud electric field of 2000 V/m, the small ion moves upward under the influence of the electric field at 0.3 m/sec or 1 ft/sec. Let us, however, consider aerosol attachment which limits the lifetime of fast ions to the order of 50 seconds or less in air full of aerosol, and up to 200 seconds in country air. In country air the ions will move under the influence of the electric field for only 200 x 0.3 or 60 meters vertically, after which time they are under

the influence of the vertical and horizontal wind alone. Clearly this small distance of 60 meters is negligible when considering updrafts and hence, we can assume that these ions take approximately 25 minutes to reach 12,000 feet.

When the thundercloud becomes more mature the area over which updraft occurs is reduced and considerable downdraft occurs. The typical thundercloud then looks like that shown in Figure 2. If we assume that corona ions are released from the region of maximum updraft, 'A' in the figure, then these ions would take approximately 45 minutes to reach the main charge center at 4000 meters considering updraft alone. Ion mobility for 200 seconds in a field of 10,000 V/m would lower this time by only 1 minute. Furthermore, the average horizontal motion of a typical thundercloud is 6m/sec, hence in a 44 minute period the cloud will have moved 16 km. Clearly, the corona point will have virtually no influence on the main charge center of the cloud, because the updraft is much too low and the cloud's horizontal motion is significant.

The horizontal surface winds under a thunderstorm can be extremely severe and can often reach speeds in excess of 25 m/sec. In the next chapter the theoretical investigations of the corona process discusses the motion of ions in wind speeds up to 15 m/sec and likens the situation to a factory chimney. In such a situation the smoke indicates the effect that horizontal wind can blow the ions well downstream and that the updraft is comparatively small. Added to this updraft will be the even much smaller vertical component due to ion mobility.

The classical theory on the currents released by corona from grounded objects under the electric field of overhead thunderclouds, indicates that these currents form part of the atmospheric electric circuit of the thundercloud which should be considered a generator of current and not of voltage. Consequently, modification of the distribution of this current by the erection of artificial passive discharging points or arrays will not have any effect on cloud electrification or the incidence of natural lightning.



Thunderstorm cell in mature state (Byers and Braham, 1949)

Figure 2. Thunderstorm Cell in Mature Stage Showing Updraft Region and Possible Ion Flow

The external dissipating current from a thundercloud is the order of 1A, but the actual charging current is several times this value, a large portion of this being dissipated internally mainly by conduction. The values quoted are for a whole storm which normally consists of several cells in various stages of development. For thundercloud dissipation to occur, no less than an additional 1A of current must pass to the cloud. If this current can reach the main charge center of the cloud from the ground which, in view of the foregoing wind investigations seems unlikely, then the dissipating arrays must be capable of dissipating an extra 1A which is in contradiction to the classical theory just examined.

It has already been pointed out in the previous chapter that corona current from single points in the field has been measured by many scientists who have reported it to be higher than multiple point corona current. The amplitude of the corona current is a function of the magnitude of the electric field, the wind speed, the radius of curvature and the height of the point. Golde[3] indicates that for a conductor several tens of meters high standing in open country, the current amounts to a few microamps. Chalmers[6] also summarizes results indicating similar values in high fields. In fact, it can be assumed from many previous findings that under very high fields and with strong winds, the corona current from a sharp point atop a 100 foot tower exceeds that from a multipoint array, and the currents are much less than 100μA.

Natural sources, such as trees are known to have given corona currents in excess of 1μA per tree with a tree separation of 3.4 m, Bent[9] and Schonland[10]. This figure is approximately equivalent to 1mA per 100 m square, implying that a 35 m square area of trees will emit more corona current than single or multiple points atop a 30 m tower in a clearing of similar area. These statements are derived from results quoted in the past by many scientists, but are also backed up by data taken during this investigation and reported in later chapters.

It has been suggested in some circles that a protective shield of

ions can be produced from dissipating arrays in order to protect the area beneath from the thundercloud charges. Such a shield would, however, be much more dangerous to the ground than the cloud above it and the suggestions cannot be viewed seriously.

The foregoing summary strongly implies that lightning incidence in an area beneath the cloud is unlikely to be affected by corona point emitters at the ground.

3.0 THEORETICAL INVESTIGATION OF ELECTROSTATIC FIELDS AND CORONA AROUND TOWER STRUCTURES

This study was performed to investigate the effect of the space charge given off by multipoint arrays in the "shielding" against lightning strikes. The problem of corona currents is an extremely difficult one to treat theoretically with many factors like point geometry, varying potentials and ion mobility entering into the picture. The wind greatly influences the corona discharge, and relationships are worked out by Chapman[11], and the space charge modifying the fields directly around the points exerts a predominating effect on the magnitude of the corona currents.

However, our intent was not to calculate the actual current values but to find the extent of the volume around various structures over which a space charge cloud could exist, and more limited even, to define a region equal to or greater than the largest possible space charge volume. Hence, it was sufficient to examine some simplified theoretical situations of corona currents given off from sharp and blunt points and of the electric fields influencing the corona under static field conditions, from which then conclusions could be drawn about dynamically changing situations.

3.1 Equations

In the theoretical calculations the tower structures were approximated by prolate spheroids, which bear good resemblance to the overall shape and are convenient for mathematical treatment. A uniform ambient electric field was assumed parallel to the vertical axis of the structures, and the structures were considered to be at ground potential. For these conditions Laplace's electric field equations were solved in elliptical or prolate spheroidal coordinates as discussed in references 12 and 13, to give the potential and potential gradient.

The resulting equation for the potential as a function of the elliptical coordinate ξ with major and minor half axes a and b is,

$$\varphi = \varphi_0 + (\varphi_s - \varphi_0)\frac{\displaystyle\int_\xi^\infty \frac{d\xi}{(\xi + a^2)^{3/2}(\xi + b^2)}}{\displaystyle\int_0^\infty \frac{d\xi}{(\xi + a^2)^{3/2}(\xi + b^2)}} = \varphi_0 + (\varphi_s - \varphi_0)\frac{I_1}{I_2}$$

The potential at the surface $\varphi_s = 0$, because the conducting ellipsoid is grounded, and the potential at height h in the unperturbed parallel field E_0 is $\varphi_0 = -E_0 h$.

$$\varphi = -E_0 h \left(1 - \frac{I_1}{I_2}\right)$$

The vertical and horizontal components of the electric field are,

$$E_V = -\frac{\partial\varphi}{\partial h} = E_0\left(1 - \frac{I_1}{I_2}\right) - \frac{E_0 h}{I_2}\frac{\partial\xi}{\partial h}\frac{\partial I_1}{\partial\xi}$$

$$E_H = -\frac{\partial\varphi}{\partial r} = -\frac{E_0 h}{I_2}\frac{\partial\xi}{\partial r}\frac{\partial I_1}{\partial\xi}$$

The equation of the ellipsoid,

$$\frac{x^2}{\xi + a^2} + \frac{y^2}{\xi + b^2} + \frac{z^2}{\xi + c^2} = 1$$

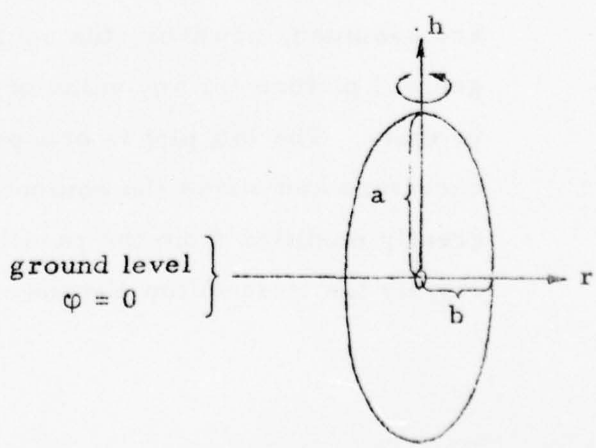
is simplified for the symmetrical case of the prolate spheroid, where the semimajor axis is a, the two semiminor axes b = c, the radial coordinate is the horizontal distance from the center of the ellipsoid $r^2 = y^2 + z^2$, and the height coordinate h = x;

$$\frac{h^2}{\xi + a^2} + \frac{r^2}{\xi + b^2} = 1 \text{ and } \xi = f(h, r)$$

The partial derivatives are,

$$\frac{\partial\xi}{\partial h} = \frac{2h\,(\xi + b^2)}{2\xi + a^2 + b^2 - r^2 - h^2}$$

$$\frac{\partial\xi}{\partial r} = \frac{2r\,(\xi + a^2)}{2\xi + a^2 + b^2 - r^2 - h^2}$$



Setting $c = a^2 - b^2$, the evaluation of the integrals yields,

$$I_1 = -\frac{2}{c^2\sqrt{\xi + a^2}} - \frac{1}{c^3} \ln \frac{\sqrt{\xi + a^2} - c}{\sqrt{\xi + a^2} + c}$$

$$I_2 = -\frac{2}{ac^2} - \frac{1}{c^3} \ln \frac{a - c}{a + c}$$

$$\frac{\partial I_1}{\partial \xi} = -\frac{1}{(\xi + a^2)^{3/2}(\xi + b)^2}$$

Hence the equations for the potential φ, the vertical component E_V and the horizontal component E_H of the electric field around a conducted grounded prolate spheroid in a parallel electric field E_0 are as follows:

$$\varphi(h, r) = \varphi\left[h, \xi(h, r)\right] = -E_0 h \left(1 - \frac{\frac{2}{\sqrt{\xi + a^2}} + \frac{1}{c} \ln \frac{\sqrt{\xi + a^2} - c}{\sqrt{\xi + a^2} + c}}{\frac{2}{a} + \frac{1}{c} \ln \frac{a - c}{a + c}}\right)$$

$$E_V = -\frac{\varphi}{h} - \frac{2 E_0 h^2}{\left(\frac{2}{ac^2} + \frac{1}{c^3} \ln \frac{a-c}{a+c}\right)(\xi + a^2)^{3/2}(2\xi + a^2 + b^2 - r^2 - h^2)}$$

$$E_H = -\frac{2 E_0 h r}{\left(\frac{2}{ac^2} + \frac{1}{c^3} \ln \frac{a-c}{a+c}\right)\sqrt{\xi + a^2}\,(\xi + b^2)(2\xi + a^2 + b^2 - r^2 - h^2)}$$

These equations were programmed and a variety of conditions were computed and plotted.

3.2 Results

Figure 3 shows 2 cases of equipotential lines around 30 m high towers of different diameter. Fair weather field conditions of 200 V/m are assumed, however, the equipotential line distribution gives the general picture for any value of the ambient field, requiring only a change in scale. The left plot is of a pointed tower having a 3.3 cm radius of curvature and shows the equipotential lines just around the tower are greatly modified from the parallel field situation. It is striking how closely the lines follow the tower along the vertical structure and how

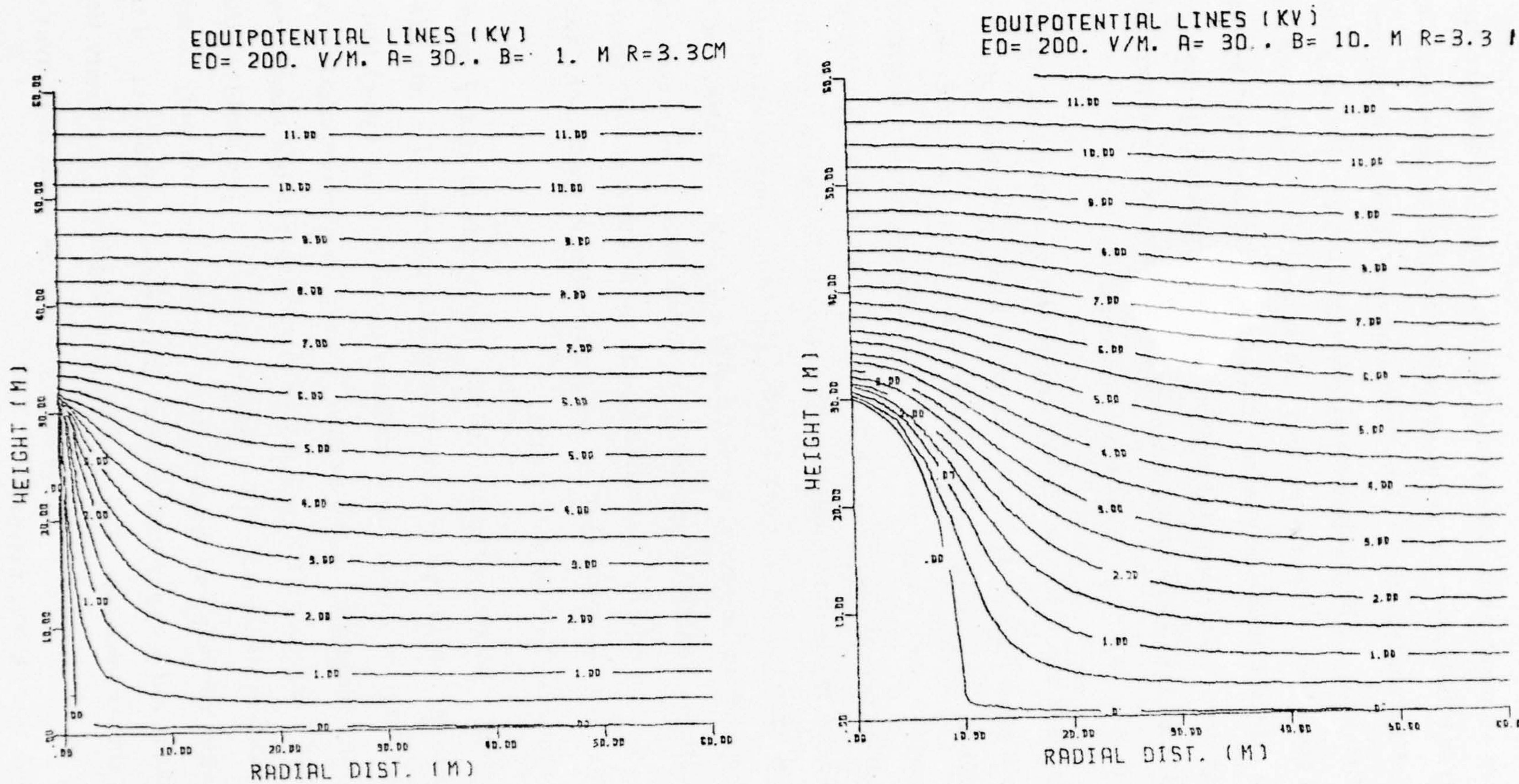


Figure 3. Equipotential Lines around Pointed and Blunt Towers

they are concentrated just around the top. But just a short distance away from the tower the parallel field situation is regained. Around the blunt structure with 3.3 m radius of curvature, the picture looks quite different. The equipotential lines are not as closely gathered around the blunt structure as they are around the pointed one, but the field is effected more at greater distances as is apparent by the line concentration. This implies that under appropriate high fields corona ionization occurs only in the immediate vicinity of the sharp point, but over a larger volume around the blunt point.

The field lines run perpendicular to the equipotential lines as represented in Figure 4. The collection area is marked off, for which the field lines terminate on the tower. If a lightning leader was coming down, and the phenomena was assumed very weak, then theoretically it would follow one of the field lines. But of course the high charge carried in a downcoming leader modifies the entire field line pattern; hence the collection area cannot be considered a lightning cone of attraction. The collection area is however, a useful piece of data indicating the distance that structures should be spaced apart in the field to be electrically uneffected by each other. This distance is quite different for the two structures, it is roughly half the height for the pointed tower and equal to the height for the blunt structure.

The direction and magnitude of the electric field at any point around the tower determines the movement of existing ions, if winds are neglected. Figure 5 is an instantaneous picture of the speed and direction of small ions indicated by the arrows, based on a mean small ion mobility of 1.5×10^{-4} m/sec at 1 V/m. At the tip of the pointed structure the ions obtain considerable speed, 300 times as high as in the ambient field, whereas atop the large round structure the ion speed is only about 3 times that obtained in the unperturbed field. Above the central part of the round structure the arrows are of about constant length and vary only little in direction, which implies a nearly constant and parallel field over an area of at least a few square meters.

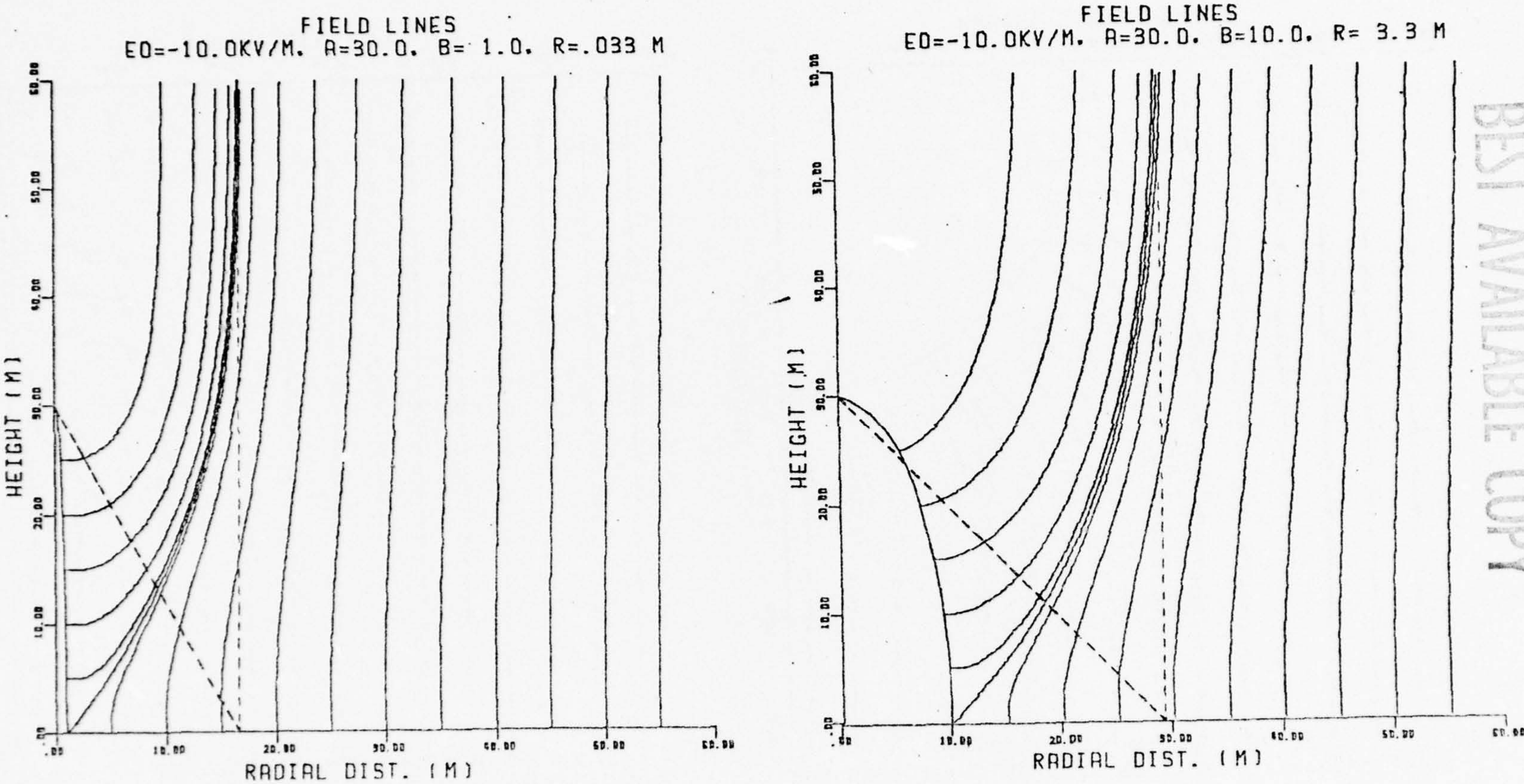


Figure 4. Electric Field Lines and Collection Area

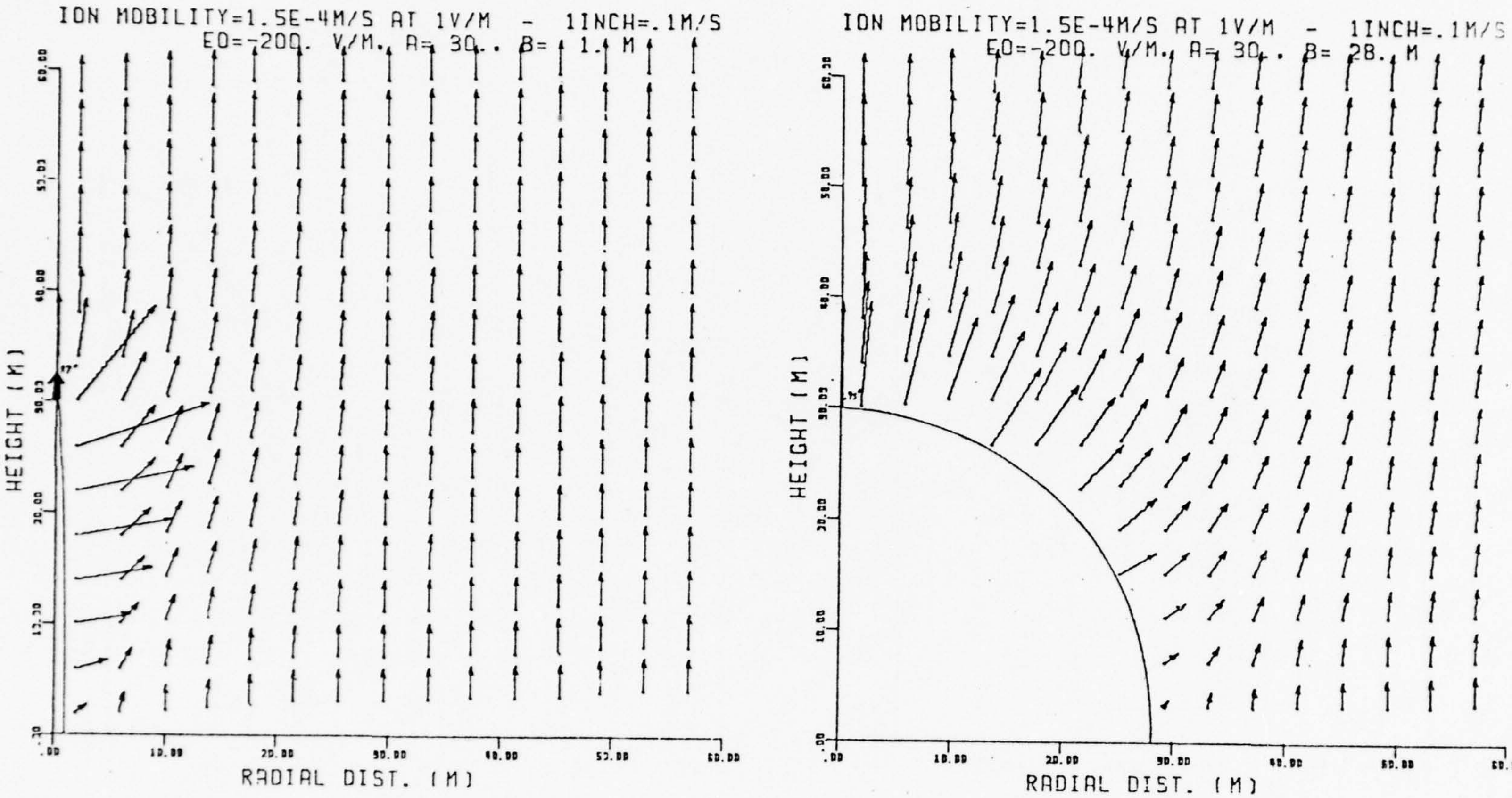


Figure 5. Instantaneous Picture of the Ion Movement

Placing now a 3 cm high point of $\frac{1}{10}$ mm radius of curvature on top of this 30 m round structure, would yield a similar picture as might be found in the center of a multipoint array. Using the information that the field can be considered constant and enhanced by a factor of 3, the situation can be paralleled to a 3 cm sharp point at ground level in a field 3 times as high as normal. Assuming storm conditions of -10000 V/m then yields the ambient field at -30000 V/m, and the equipotential lines are shown in Figure 6. The enhancement at the tip of the point is 370. Comparing this data with a simple sharp spike of the same radius of curvature as the 3 cm point placed at ground level in the stormy field of -10000 V/m, it is found that the spike would only have to be 12 cm high to give the same field enhancement of 370. Hence, neglecting wind, the corona given off by a 3 cm point atop a 30 m blunt structure is comparable with that from a 12 cm point at ground level. This suggests that the center portion of an elevated multipoint array gives off very little corona.

In Figure 7 the effects of wind on corona are studied. In this approach only horizontal winds are considered neglecting any updrafts as might exist before and during thunderstorms. The last 2 m of a pointed 30 m high tower are plotted in a storm field of -10000 V/m. Ionization along the tower surface will take place only where the field is enhanced to values greater than the breakdown potential gradient which is roughly assumed at 1 million V/m.

First, to determine the outermost boundary of a possible space charge cloud, consider the simple picture where space charge does not effect the field. Two cases for winds of 5 and 15 m/sec are shown. Under the effect of the field the ions move upward and out to the sides, and wind adds an extra horizontal component to their movement, creating a sort of concentrated line charge as the ions travel around the tower. The ion speed right at the tower is very high and drops off rapidly with distance. In the first case the markings along the ion path are reached at 150 msec intervals, in the second case at 50 msec intervals. The ions do not travel far into the wind under either situation, at most 1.25 m.

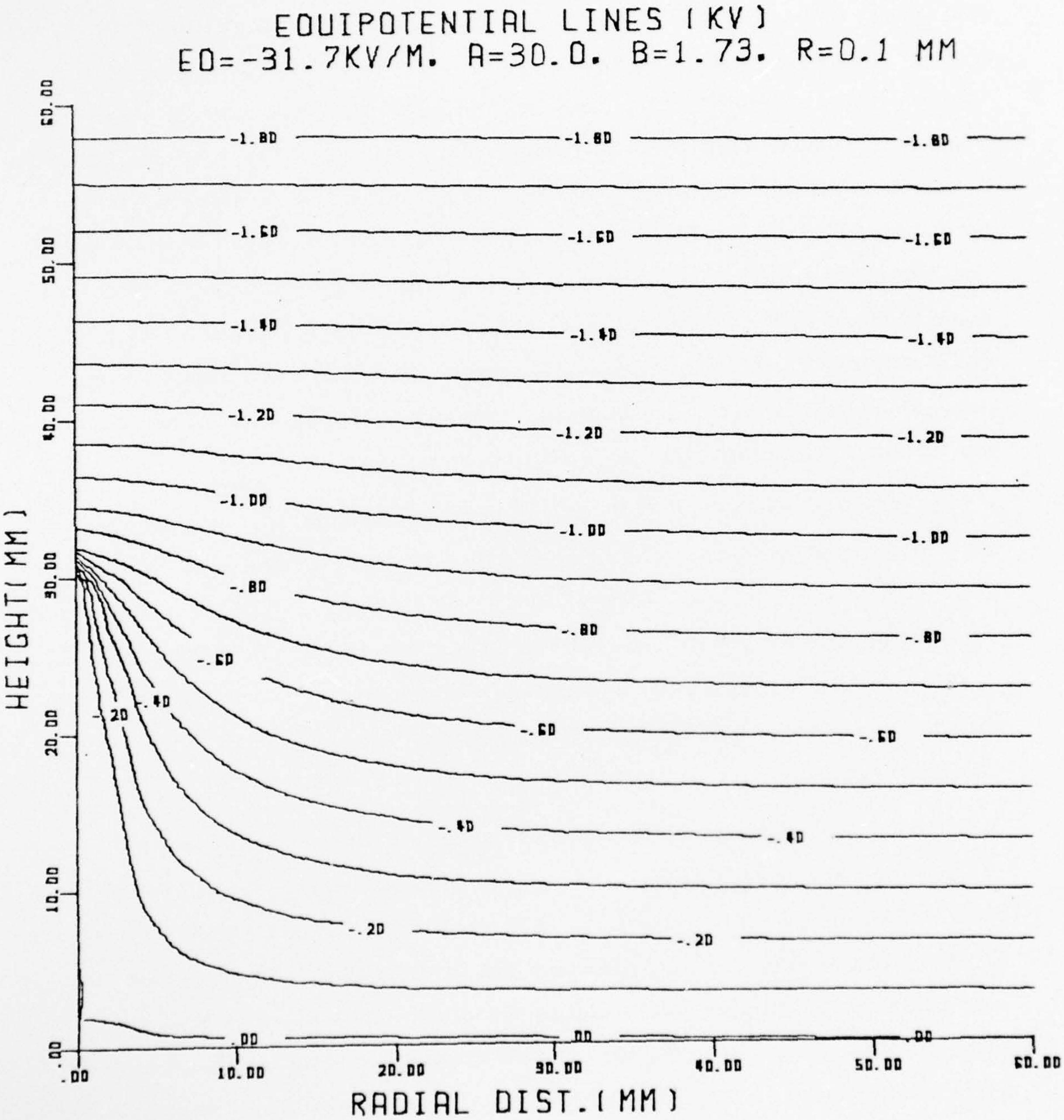
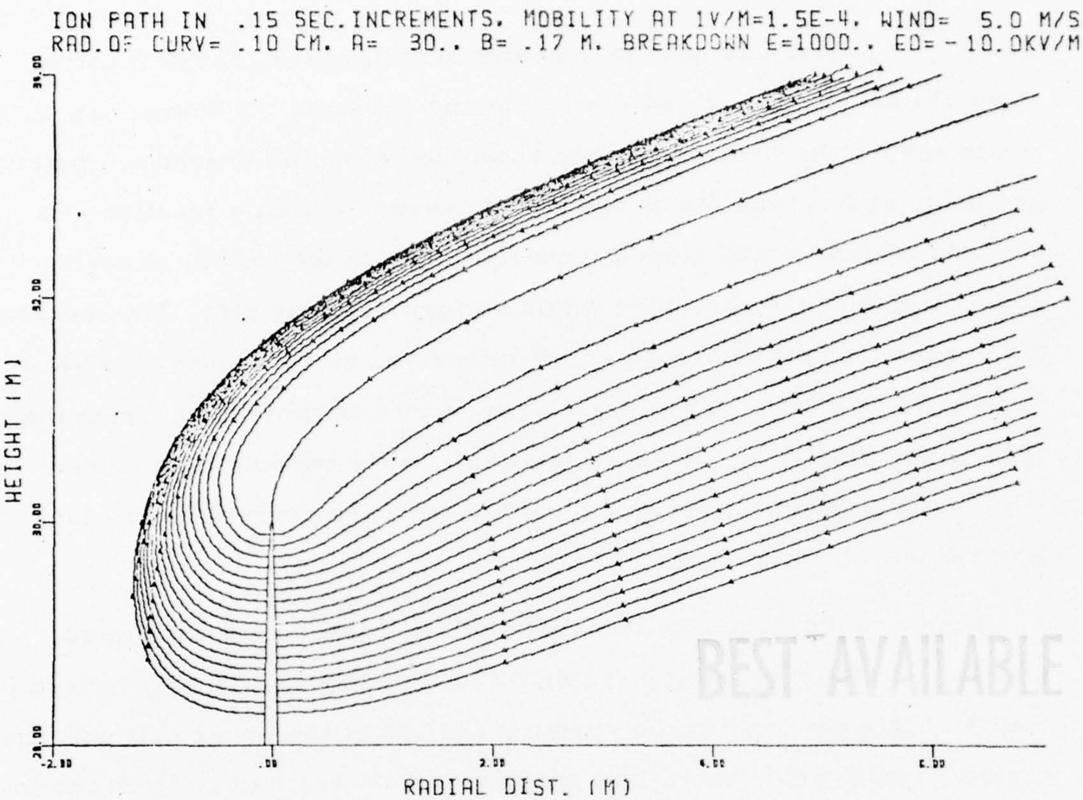


Figure 6. Equipotential Lines around a Sharp Point on Top of a Rounded Structure



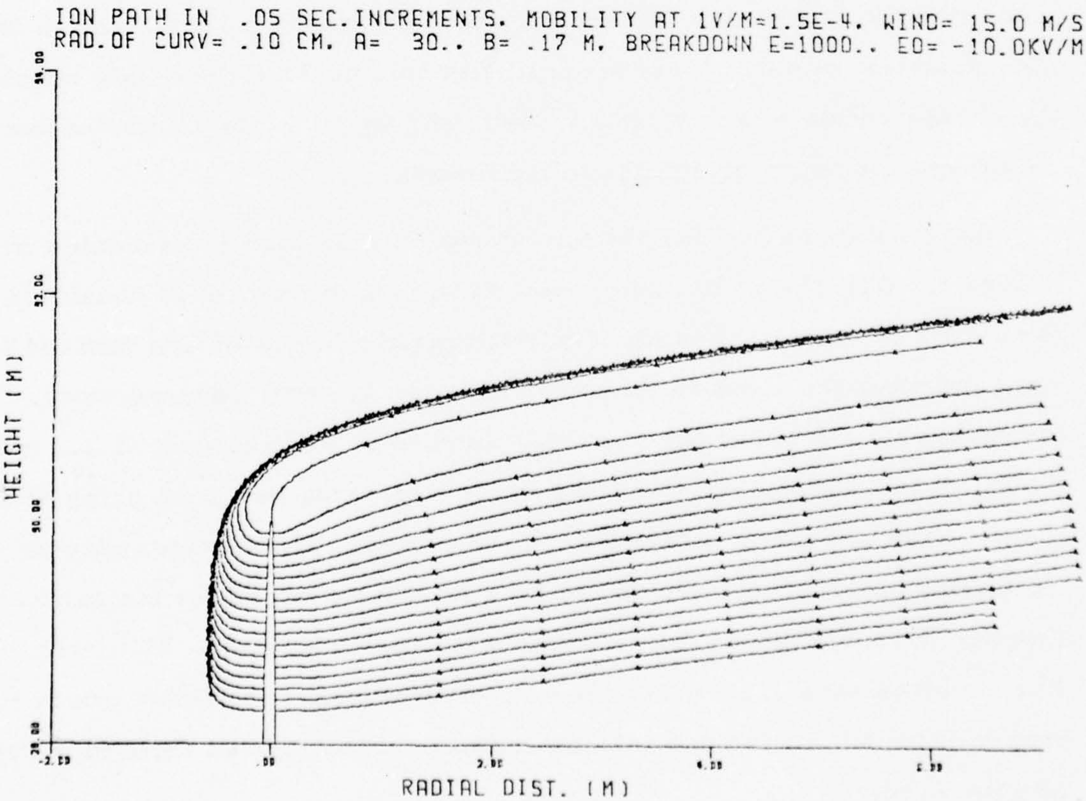


Figure 7. Ion Movement under Horizontal Winds Showing Maximum Boundary of Ion Cloud

The situation can now be considered with space charge limiting. Once corona is formed and starts moving out from the tower, its charge would reduce the field around the tower to below the breakdown potential gradient, and corona discharge would cease. Within a fraction of a second the wind would blow the charge clear of the tower, exposing it again to high fields, and ions would be formed again etc. This causes the corona currents to be given off in bursts, as first observed by Trichel in 1938[14]. When each layer of ions is moving out from the tower, the wind is the dominating effect, since the field is reduced, and the top graph would under this dynamic situation be modified to look more like the one on the bottom.

Hence, under any condition ions will not escape the maximum boundaries shown in the top graph. The ion cloud would only expand less than 1 m into the wind at the very top section of the tower that goes into corona, and it would move in a near horizontal trail away from the tower much like the smoke of a factory chimney, where the upward motion is comparatively small. A corona trail like this could not possibly reach the charge center of an overhead cloud, nor would it yield a protective shield against lightning strikes to the tower.

More detail on how far the ions move into the wind is presented in Figure 8. Only the radial component of the ion movement is considered for values of horizontal wind. Double logarithmic scales are utilized to show the situation close to the tower and also at some distance away. Starting from the tower top upwards, conditions were examined $\frac{1}{10}$ mm, 1 mm, 1 cm, 10 cm, 1 m above the tower; the same was done going down from the top and going outward from the center. The discontinuity in the center of the graph, where the data sets are merged, is insignificant. Contour lines are drawn for different wind speeds from 5 - 25 m/sec. The enclosed area represents the only region around the tower where ions have a resultant horizontal velocity component that allows them to move into the wind.

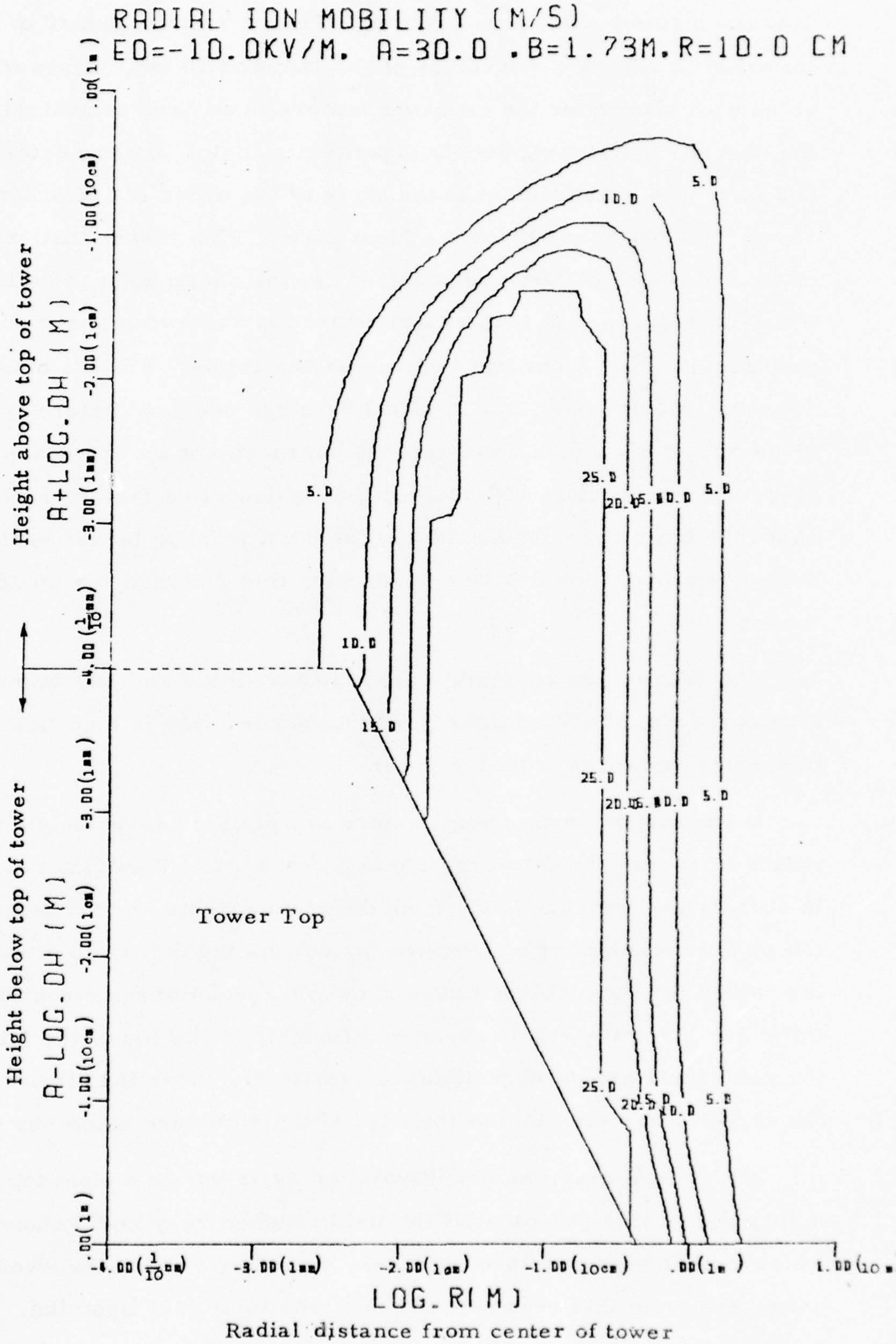


Figure 8. Expansion of Ion Cloud into Wind

The exposure factors help determine how soon and out to what distance a tower will go into corona. Figure 9 shows two 30 m high towers with radius of curvature of $\frac{1}{10}$ mm and 10 cm. Lines of equal value were drawn for the exposure factors in an area around the top of the towers, again using double logarithmic scales to show detail near and far. The enhancement at the tip is of the order of 10000 for the sharp point but only 100 for the blunt point. This means that only fields of the order of 100 V/m are required for the sharp point to be in corona, which is in agreement with experimental results from a sharp point giving up to $\frac{1}{4}$ μA current in fair weather fields. For the blunt point however, storm conditions of 10000 V/m are required before corona is given off. It should be noted that the enhancement for the sharp point drops off very rapidly with distance, it is down to a factor of 10 only 30 cm above the tip. The enhancement of the blunt point is larger at these distances and drops down to 10 only at twice this distance, or 60 cm above the top.

The sharp point goes into corona in low fields and just immediately around the tip, the blunt point goes into corona only in high fields but out to greater distances from the tower.

In Figure 10 the exposure factors are plotted versus height for 2 values of radius of curvature, 1 mm and 3.3 cm. This data can be useful in correlating measurements from different heights, or for determining the minimum height of a structure for corona breakdown to occur, given the values for the ambient field and the sharpness of the structure. The thick line gives the enhancement relationship at the top of the structure, the solid lines are valid at distances vertically above the structure, and the dashed lines are valid at the edge of the structure below the top.

The overall shape of a multipoint array is that of a blunt top. Hence it may not go into corona until the field reaches very high values, at which time it may go into corona over a greater volume than would a sharp point, and from this argument it could tend to attract lightning. However

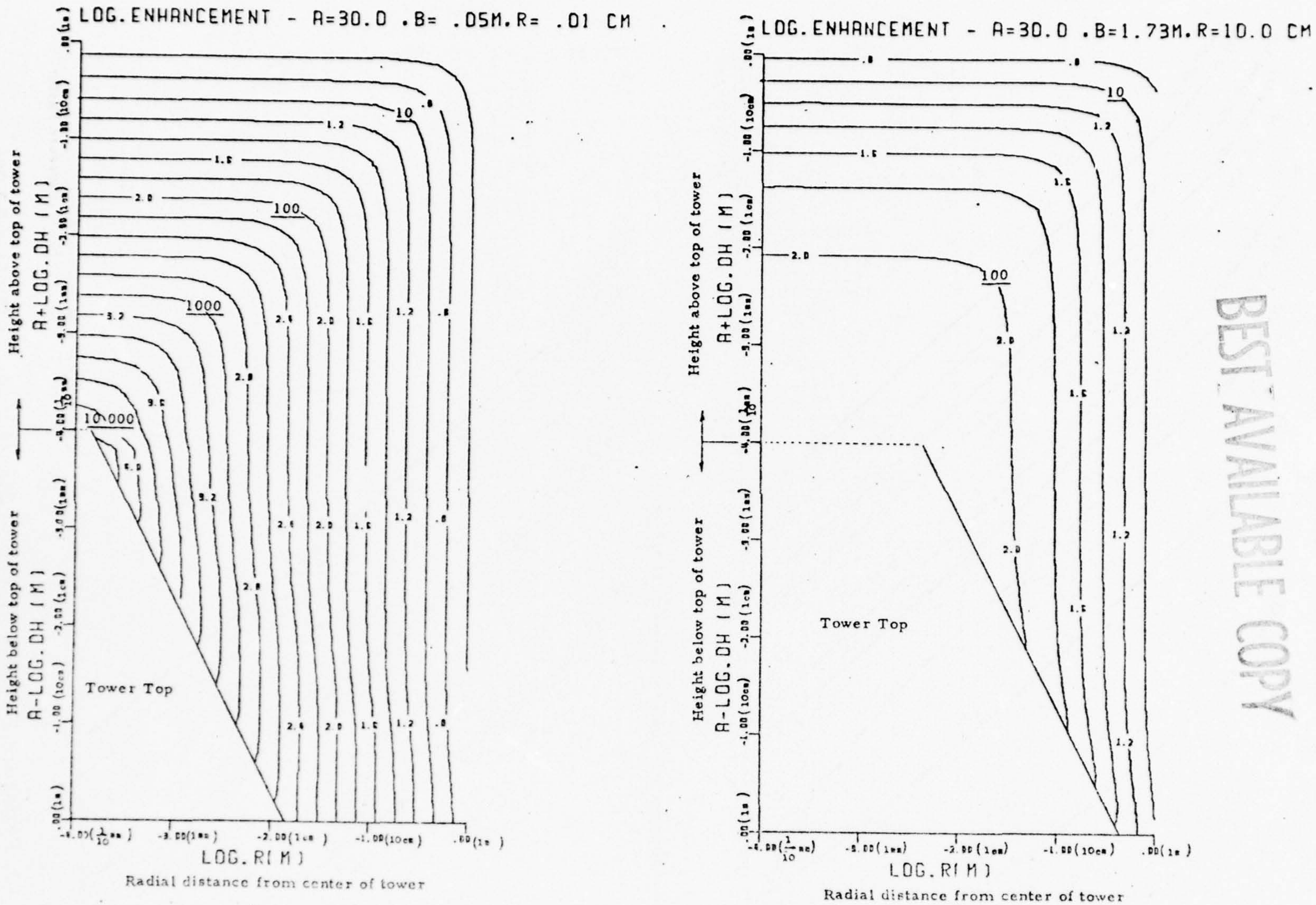
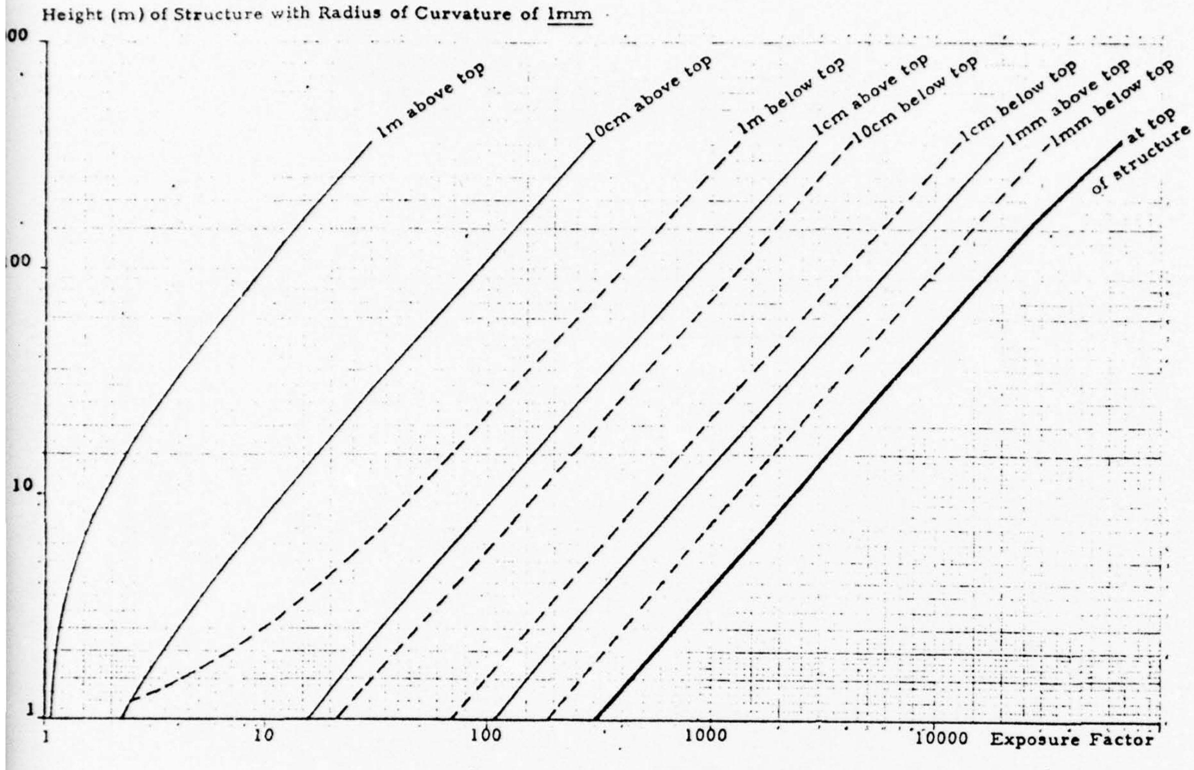


Figure 9. Lines of Equal Value for Exposure Factors around Sharp and Blunt Structures



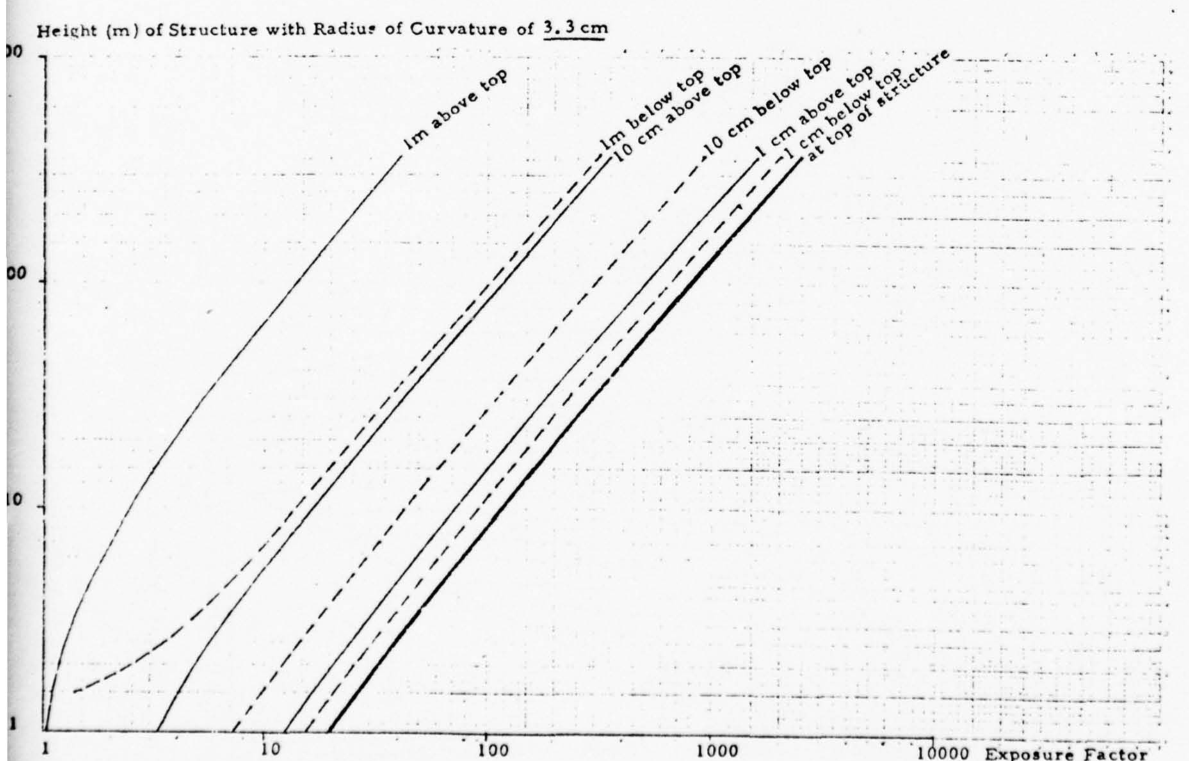


Figure 10. Exposure Factors at Top of Structures, Vertically above, and below at Side of Structures

the effect of the many sharp points and the presence of space charge would modify the picture here and cannot be neglected, but their influence is very difficult to estimate.

Another hypothesis supports the properties of such an array reducing the number of strikes to a very tall structure. In such a situation the upward going leaders, which may be dominant on structures in excess of 600 feet, may be reduced if the overall corona discharge emanates from all the points on the array. This would tend to put the array in a glow situation and reduce the tendency for a glow to arc discharge initiating an upward going leader. Theoretically the idea sounds feasible but in practice it is, no doubt, almost impossible to build an array over which the electric field is uniform at all points and where the corona space charge does not shield the other points on the array. Some reduction in the number of upward leaders may however be possible with careful design. The present tower arrays however would not meet the necessary design qualifications, as the electric field around their extremities would be very large.

In measuring the corona currents given off by multipoint arrays, standard air terminals and similar conductors, one has to consider that the instantaneous measurement of the apparent current cannot be expected to give an accurate value of the true corona current. The sudden changes in the potential gradient of the electric field give rise to displacement currents which do not involve any charge transfer. These rapid field changes are linked to lightning discharges and give sudden excursions superimposed on the true corona current recordings.

Some theoretical calculations were performed to give an estimate of the size of the displacement current as a function of the tower height, the radius of curvature and of the field change. The displacement current I_d is related to the rate of change in the ambient electric field E_0 by

$$I_d = \epsilon_0 \frac{d}{dt}\int E \, dA = \epsilon_0 \frac{dE_0}{dt}\int Enh \;\; dA,$$

where the integral depends on the shape of the structure, dA is an area

element, E is the electric field and Enh is the enhancement both at the surface of the conductor. The tower shape was assumed ellipsoidal and the integration was performed only over the top segment of 5 cm height to reflect the influence of an overhead storm, for which the effect of the change in an assumed parallel field condition on the vertical segments of the tower is extremely small.

In Figure 11 the displacement current is given per unit of time rate of change in the ambient field, increasing in magnitude with the structure height as it goes from 1.5 to 360 m. The displacement current also increases with the radius of curvature, which in effect enlarges the surface area exposed to the field. In Figure 12 the displacement current is plotted against the rate of change in the ambient field for 30 m high structures with both sharp and blunt tops. With Uman's [22] theoretical value for the field change due to a close lightning flash of 180 V/m in 1 μsec, displacement currents of 2 to 7 mA would result. Much larger experimental values of field change are often recorded, by a factor of at least 10 or 100 higher than the theoretical numbers, which would give rise to proportionately larger displacement currents.

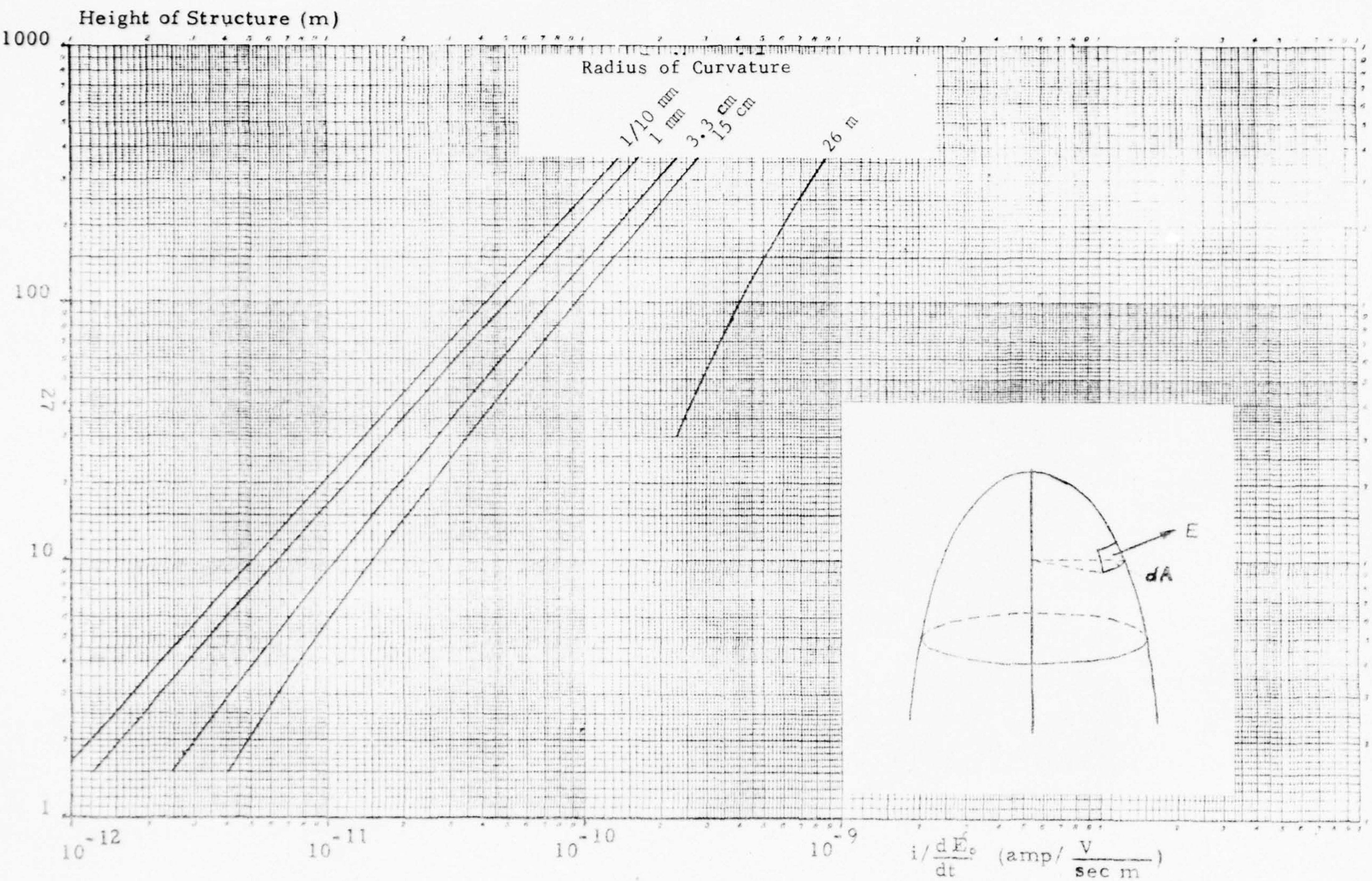


Figure 11. Ratios of Displacement Currents and Rate of Change in Ambient Electric Field

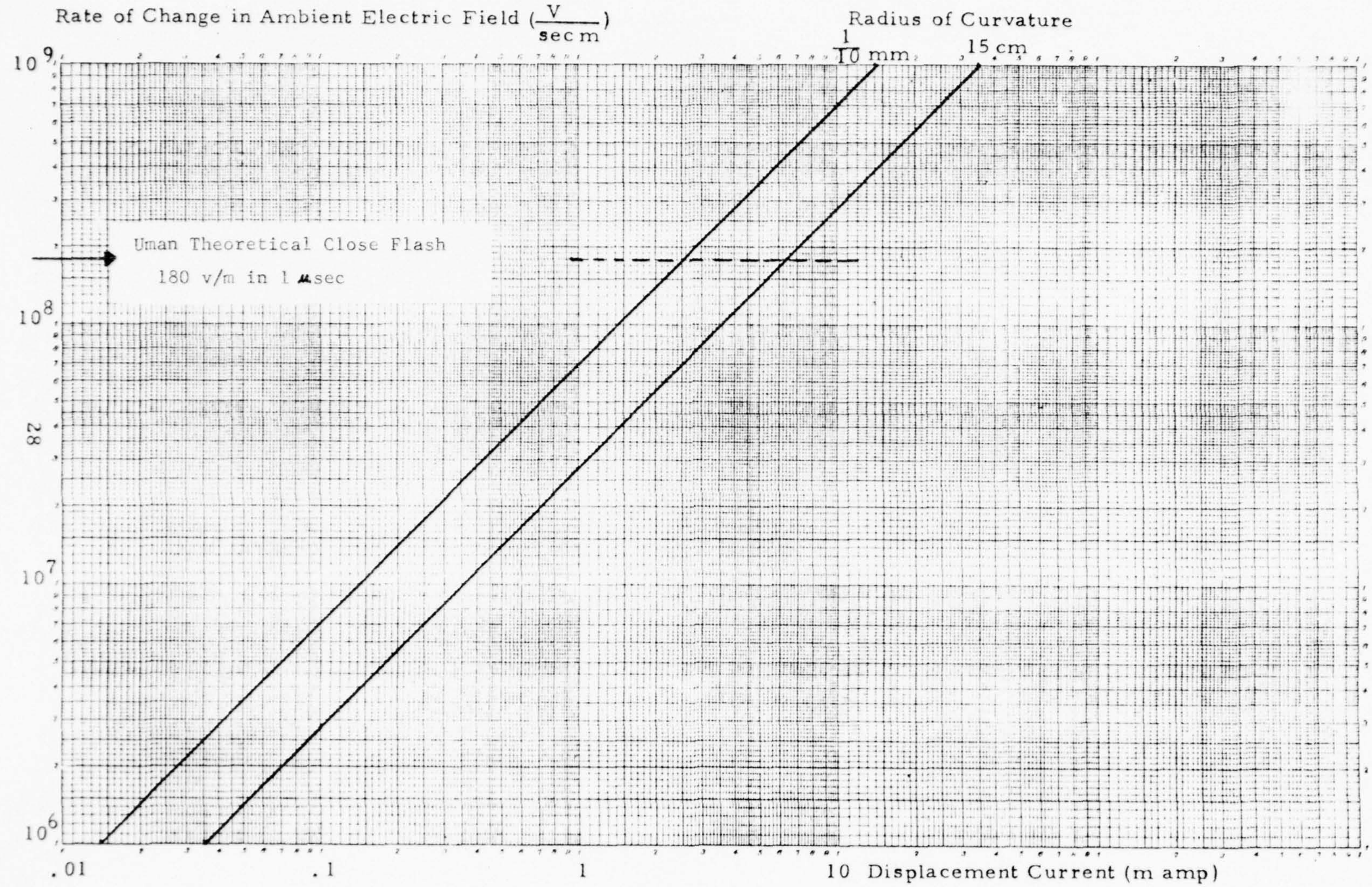


Figure 12. Displacement Currents for 30 m High Structures

4.0 STATISTICS OF LIGHTNING STRIKES TO GROUND

A normal negative lightning leader advances toward the ground in discrete steps until it reaches a distance of a few tens of meters above the ground. When the leader is at that height the field at the ground is very high and counter streamers are initiated from various points on the surface. One of these streamers will join up with the downward coming leader to form a path for the large return stroke. It is therefore at that particular distance that the point of strike is determined. This striking distance is defined as the distance between the tip of the lightning leader and the point to be struck at the instant of time when the counter streamer meets the downward leader.

An excellent photograph of the striking distance phenomena just described is shown in Figure 13 where lightning is striking a 500 foot tower at NASA/KSC. This photograph was supplied by NASA/JSC, Houston. At the time of the strike a multipoint array was on top of this tower, but according to the manufacturer the galvanizing process had not been performed properly and the array was not working; it was replaced shortly afterward. The influence of the metallic conductor on the ion formation is discussed in Section 5.1.

For a negative polarity stroke the striking distance varies from about 30 m at 20 kA to 150 m to 150 kA. The striking distance for the rare positive polarity strokes is about 50% larger than that for the negative polarity strokes. Hence, the striking distance increases with the severity of the discharge and for an average 25 kA strike it is about 40 m. More important, however, these results and associated theory show that the progression of the leader remains quite unaffected by any feature on, or below ground, until the tip of the leader has reached a height of only a few tens or, at most, two hundred meters above ground.

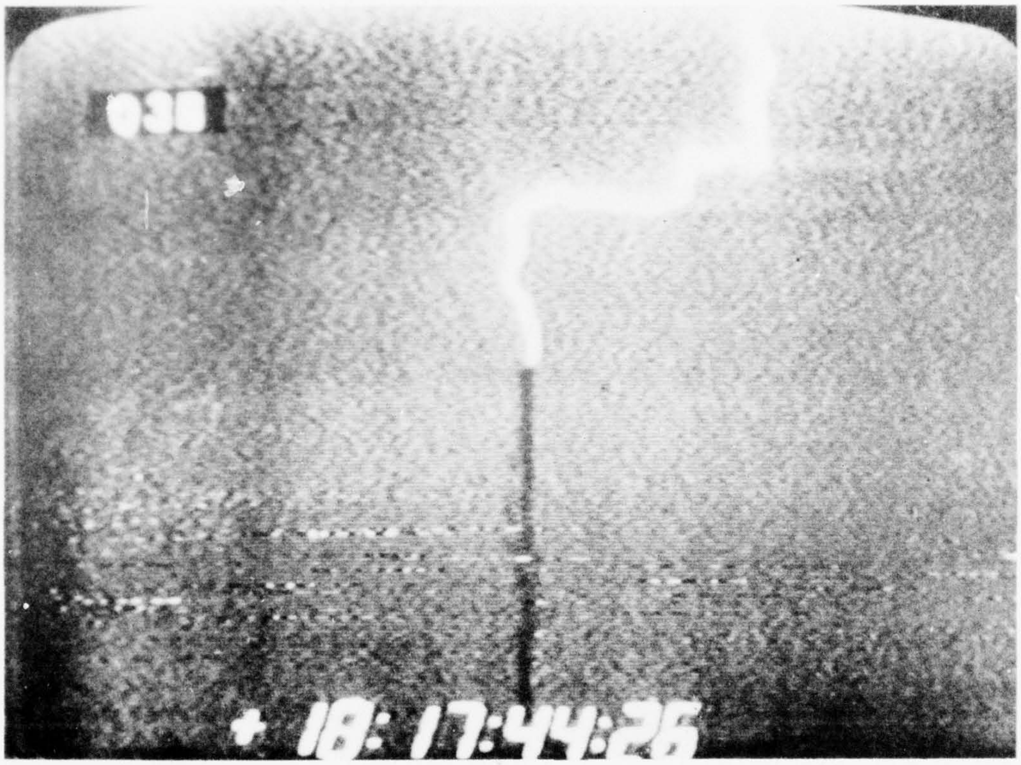


Figure 13.

Lightning striking a 500 foot meteorological tower at NASA's Kennedy Space Center, Florida, and hitting the dissipation array

These results therefore provide quantitative evidence against the belief in lightning attraction areas and cast considerable doubt on any local influence by dissipation arrays.

Cianos and Pierce[19] give a useful relationship for determining the frequency of strikes under a thunderstorm. They conclude that the number of thunderstorm days per month, T_m, and the flash incidence per km^2 per month, σ_m, are related by the equation:

$$\sigma_m{}^2 = aT_m + a^2 T_m{}^4$$

where a equals 3×10^{-2}. The ground flash incidence per km^2 per month is quoted as $p\sigma_m$, where p is the proportion of flashes that go to ground. As an example, p = 0.18 in Orlando and 0.30 in North Dakota.

Considering the frequency of strikes to tall structures electrically connected to ground, Pierce and Price[20] have provided more useful data. They indicate that the attractive radius, r_a, and its associated attractive area $A_a = \pi r_a{}^2$ are primarily functions of the structure height h. The attractive radius is defined as the average radius at which a downward leader from the cloud is just able to induce an upward streamer from the structure that will unite with the downward leader and thus divert the flash to the structure. The triggering factor represents the inclination of flashes to be initiated at the tip of the structure; it is negligible for $h \leq 100$ m, but as h increases, triggered flashes become increasingly common and for $h \geq 250$ m the triggered variety of discharge is by far the more important.

Cianos and Pierce[19] indicate that it is difficult to calculate r_a but give a complicated expression for r_a as a function of h. Their expression is based both on mathematical representations emerging from theoretical analysis, and on a weighted empirical fit. Table 1 shows their results. Note however that above 150 m the attractive radius does not change with a further height increase. This is because calculations

indicate that for h ≧ the field distribution between the tip of the structure and the downcoming leader is not much influenced by the presence of the ground.

Pierce has discussed the instances relating to triggered lightning, and assumes that it may occur when the ambient electric field lies between 3 and 30 kV/m and the voltage discontinuity between the tip of the conductor causing the triggering and the unperturbed atmosphere is 0.3 to 6MV. The longer these values are maintained and the larger the values, the more likely the possiblity of triggering a flash.

Pierce and Price[20] have summarized the best presently available data on the incidence of triggered lightning as a function of height in Table 2. The data base is so scanty that substantial future modifications could occur. Also shown in Table 2 are the information derived from two expressions by Pierce and some theoretical results due to Horvath.[21] None of the theoretical expressions agree well with the experimental data. Horvath's work much overestimates the incidence at lower values of h, and gives underestimates for high h. Equation (1) fits well for h ≦ 150m but overestimates for large h.

As an example let us consider the 1200 foot or 365m tower at Eglin Air Force Base then "protected" by a dissipation array. Table 1 gives the attractive radius as 400m and Table 2 indicates an average

Table 1

Relation Between Structure Height (h) and Attractive Radius (r_a)

h (m)	r_a (m)
25	~150
50	~250
100	~350
150	~400
> 150	~400

value of 10.5 for the ratio of triggered to natural lightning. The incidence of flashes to ground at Eglin Air Force Base is approximately 7.5 km^2. Thus, the annual incidence of natural lightning to the tower should be:

$$7.5 \times \pi \times (400)^2 \times 10^{-6} = 3.77$$

Triggered lightning should contribute a further incidence of some

$$10.5 \times 3.77 = 39.6 \quad .$$

The total number of strikes to the tower will therefore be on the order of 43 per year, of which the majority are upward initiated.

Table 2

Proportion of Triggered to Natural Lightning

Structure Height (m)	Actual Data	Expression (1)	Expression (2)	Horvath Theory
50	~0	~0	~0	0.1
100	~0	~0	~0	0.2
150	0.3	~0	0.5	0.4
200	1	0.1	2.8	0.7
300	4	1.3	16	1.4
400	10	6	38	3.0

Equation (2) underestimates throughout, but the agreement is becoming better for h ~ 400 m.

5.0 REVIEW OF RESULTS FROM A PRACTICAL APPROACH TO MULTIPOINT DISSIPATION ARRAYS FOR LIGHTNING PROTECTION

The principle of the dissipating system is described in reference 17 where the following three statements suggest a reason for the "success" of multipoint arrays in preventing lightning; such achievements are, however, disputed from the scientific point of view.

"1) The cloud charge is reduced to some degree, in proportion to the flow of current.

2) The potential gradient between the cloud and the protected area is reduced by the flow of ions through the intervening air space.

3) The mass of ions produced act as a form of Faraday shield."

A practical approach to the idea of lightning protection by use of multipoint arrays has been pursued by the U.S. Government in the installation of dissipation array systems at a number of sites. This study has been initiated to use a scientific approach to examine the performance of some of these systems and furnish an explanation of their functioning. The facilities provided for the experimental side of this investigation within the contract and with agreement with other agencies were the C9 site at Eglin Air Force Base, Florida and the NASA/GSFC tracking stations at Rosman, North Carolina and at the Merritt Island Launch Aquisition (MILA) facilities, Kennedy Space Center, Florida. These locations were all equipped with lightning elimination and dissipation arrays as provided under contract to these agencies by Lightning Elimination Associates (LEA). Studies were made on the final reports to these agencies, reference 16, 23 and 25, and correlations were performed on the acceptance test results presented therein.

5.1 Description of Dissipation Array Types

The arrays in use at these sites are of various designs with the

basic idea of many sharp points for corona dissipation over the area of the array. There are in general two types of material. One is termed dissipating wire which looks similar to barbed wire, and measurements have shown typically 4 points 2cm long separated by approximately 90° around the wire and spaced every 7 cm along the wire. The other material is formed on a rigid metallic panel with protruding sharp points and is similar to what one may expect in a fakir's bed of nails. The conducting material typically has 4 cm high sharp points separated by 6 cm. The type of conducting material is unimportant by the following argument. The electric field lines around the point are unaffected by the material type if it is at ground potential, and the avalanche process causing the ion formation occurs in the high field around and outside the point. Hence, the material type cannot effect the corona density and only the fact that it is conducting and the sharpness of the points matters.

Dissipating wire is used to form the umbrella array, the truncated cone and the barrier types of arrays, whereas the rigid conducting material forms a disc or panel array. Figures 14 and 15 show an umbrella array installed on a 100 foot collimation tower at the NASA/GSFC MILA site. It is approximately 20 feet in diameter and is comprised of about 1000 feet of dissipating wire wrapped spirally around the framework.

A barrier array, as installed at NASA/GSFC Rosman, is shown in Figure 16. Its height is 40 ft, it has seventeen strands of wire each of length 170 ft and separated by about 1 ft giving a total wire length aproaching 3000 ft. Such an array can house any length of dissipation wire. A truncated cone array located at the Rosman station is shown in Figure 17 below an umbrella array. It is made up of a number of dissipating wires formed around the tower in guy rope fashion. A considerable portion of the dissipating wire is, however, in a region of reduced electric field, hence lowering the overall amount of corona current produced. In another arrangement dissipating wire is passed around the roof perimeter of a building, as is shown in Figure 18 also at the NASA/GSFC Rosman facility.

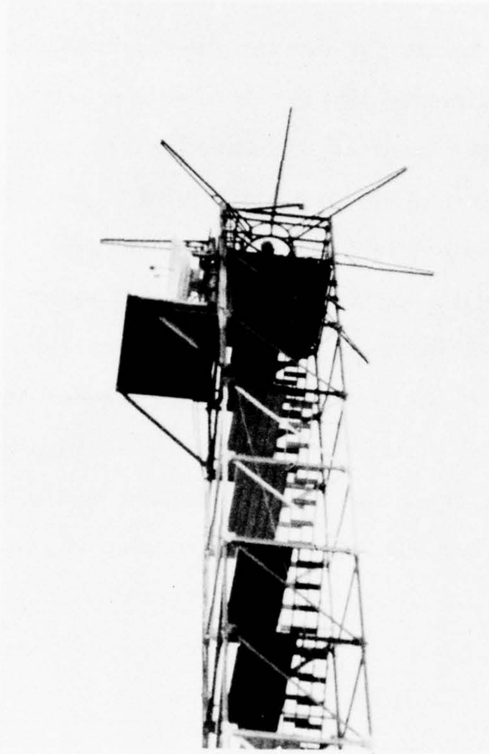


Figure 14. Umbrella array at MILA

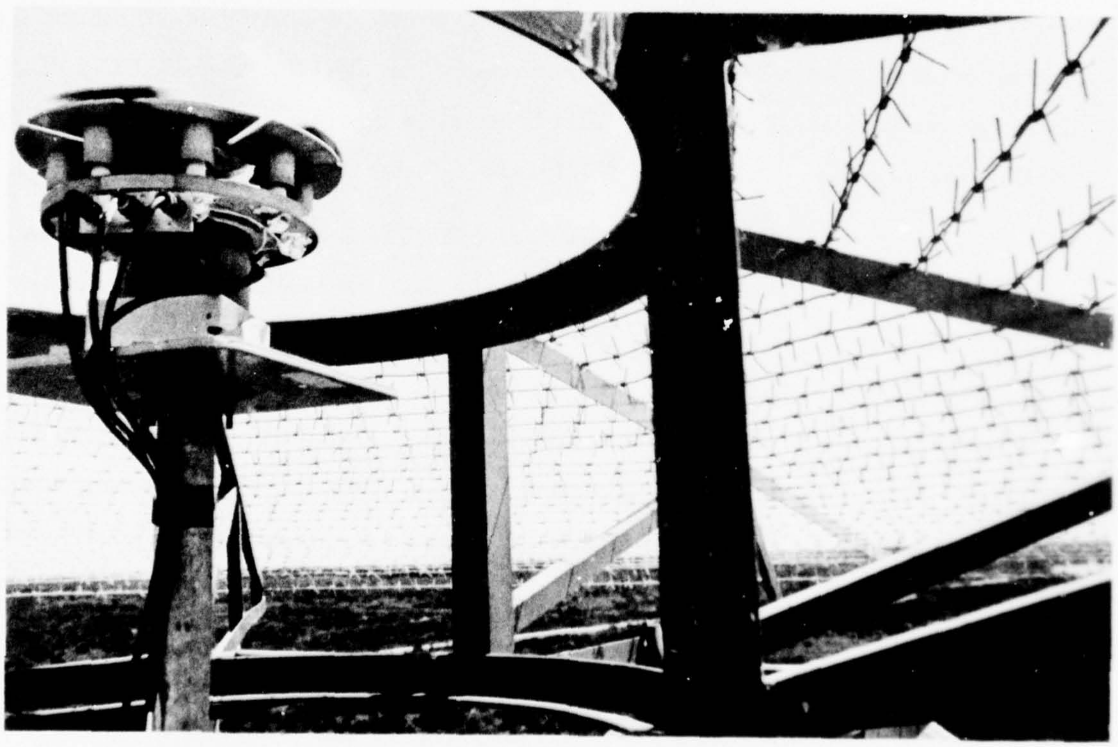


Figure 15. Close up of umbrella array at MILA

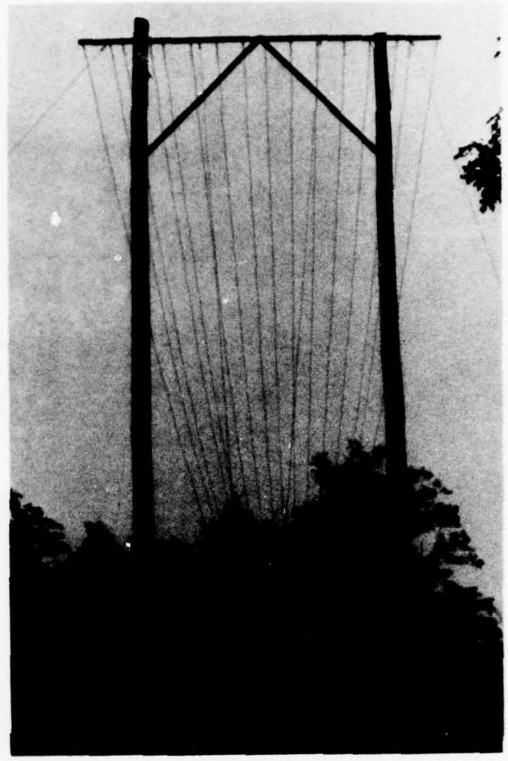


Figure 16.
Barrier array at
Rosman, N.C.

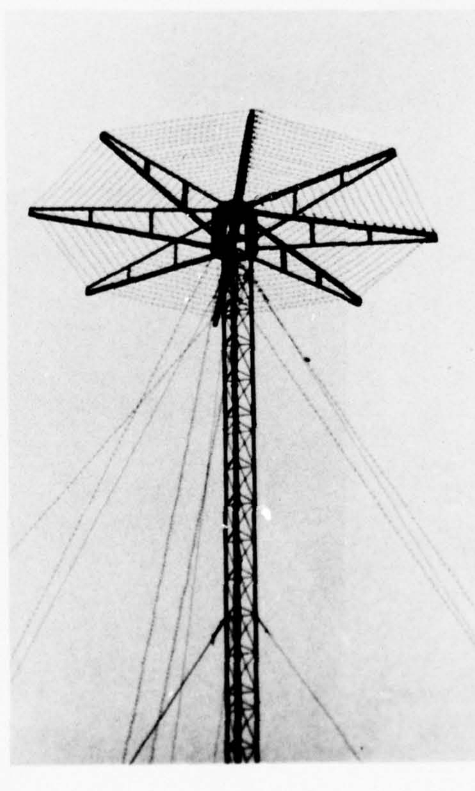


Figure 17 .
Guy rope dissipation
wire added to an array
at Rosman, N.C.

Figure 18.

Perimeter array at Rosman, N.C.

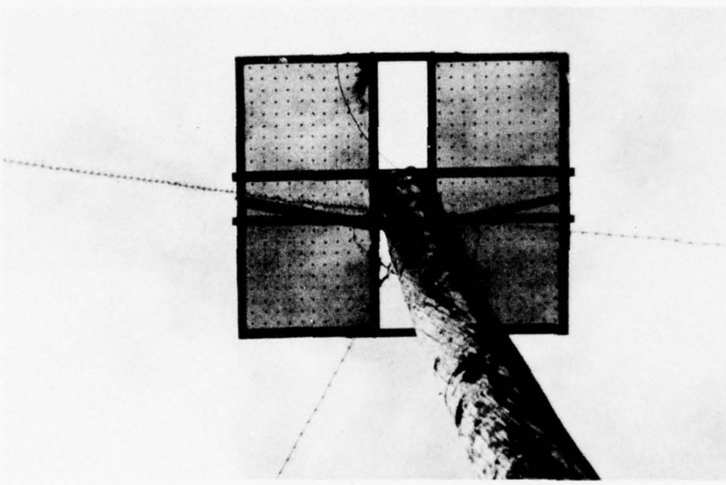
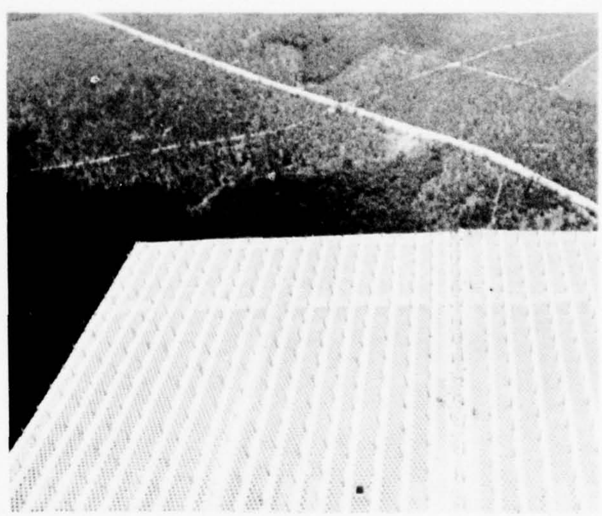


Figure 19.

Panel array at site C74, Eglin A.F.B., Florida

Figure 20.

Panel array atop 1200 foot tower at site C9, Eglin A.F.B., Florida



Panel arrays are shown in Figures 19 and 20 atop a wooden pole at site C74 Eglin AFB and on top of a 1200 ft tower at site C9 Eglin AFB. The close-up shows one out of 3 panels each measuring 4' x 6'.

5.2 Quotes on Dissipation Array Performance

An article in the Journal of Electrical Construction and Maintenance[15] states the purpose of the dissipation arrays as follows:

> "Rather than attempt to minimize lightning-caused damage and outages by shunting the lightning discharge across a spark gap or arrestor, this method is designed to prevent lightning strikes and the accompanying secondary effects. Basically, a dissipation array is set up to slowly bleed off the electrostatic charges contained in a thunderstorm, thus preventing the buildup of a potential gradient sufficient to result in a strike."

> "The system installed at Eglin Air Force Base protects a UHF transmitting antenna mounted atop a 1200 ft tower situated on an 800 ft hill, the highest land point in Florida. Prior to the installation, lightning strikes at this site averaged over 100 per year. In the 18 months since installation, there have been no strikes.
>
> Measurements were made to determine array dissipation current levels and ground voltage suppression at varying distances from the tower. Array currents up to 150,000 μA were recorded with energy dissipation between strokes often up to 18 coulombs. The protective influence of the array was found to extend over an area with a radius of at least 1200 ft. Tests indicated that cloud cells were significantly influenced 1/4 mile from the site."

The final report[16] on the 1200 ft tower array system at Eglin AFB states that the dissipation array:

"1) Actually prevents the lightning stroke.

2) Dissipates the same energy levels as in a stroke, but slowly over a period of time."

The first statement is contradicted by the experimental investigation in Section 7, and the second point is meaningless without specification of a time period.

The arrays are not devised just to protect the structure on which they stand, but in many cases the area surrounding them as well. At the NASA/Rosman facility the dissipation array system was to provide protection from lightning strikes over an area of about 180 acres, and in a design study [18] the array installation was to prevent lightning strikes to the region inside an airport of 412 acres.

5.3 Correlations and Review of Published Corona Current Data

The acceptance test results from the dissipation arrays at Eglin AFB, at NASA/GSFC Rosman and at NASA/GSFC MILA, as presented in references 16, 23 and 25, were examined. The presented data was checked for consistency with itself, it was compared with newly recorded data from the same installations for a reasonable range of values, and it was correlated with an independent data analysis performed on some of the same original data. Also several installations were tested for possible insulation breakdown between the arrays and the towers. Such breakdown was found at Eglin and MILA and could have induced errors into the corona measurements had this condition existed at the time of the recordings.

The conclusions are that much of the corona data from different types of dissipation arrays presented in these reports is grossly in error. There have been errors in reducing the data, errors in believing displacement currents are corona currents, errors in the grounding circuits that give rise to Telluric currents in the circuit. In order to illustrate these points two instances per site are presented below, however, there are many more similar questionable results.

Figure 21 is taken from reference 16 and supposedly shows corona current from the 1200 foot tower dissipation array at Eglin AFB. The top and bottom trace are both labeled 500μ A/division and yet a peak value of 7500μA positive and a peak value of 28,000μA negative are represented by exactly the same deviation. Also the displacement currents due to lightning appear to be reversed in time sequence. The slower corona current buildup should take place after the discharge and not before it.

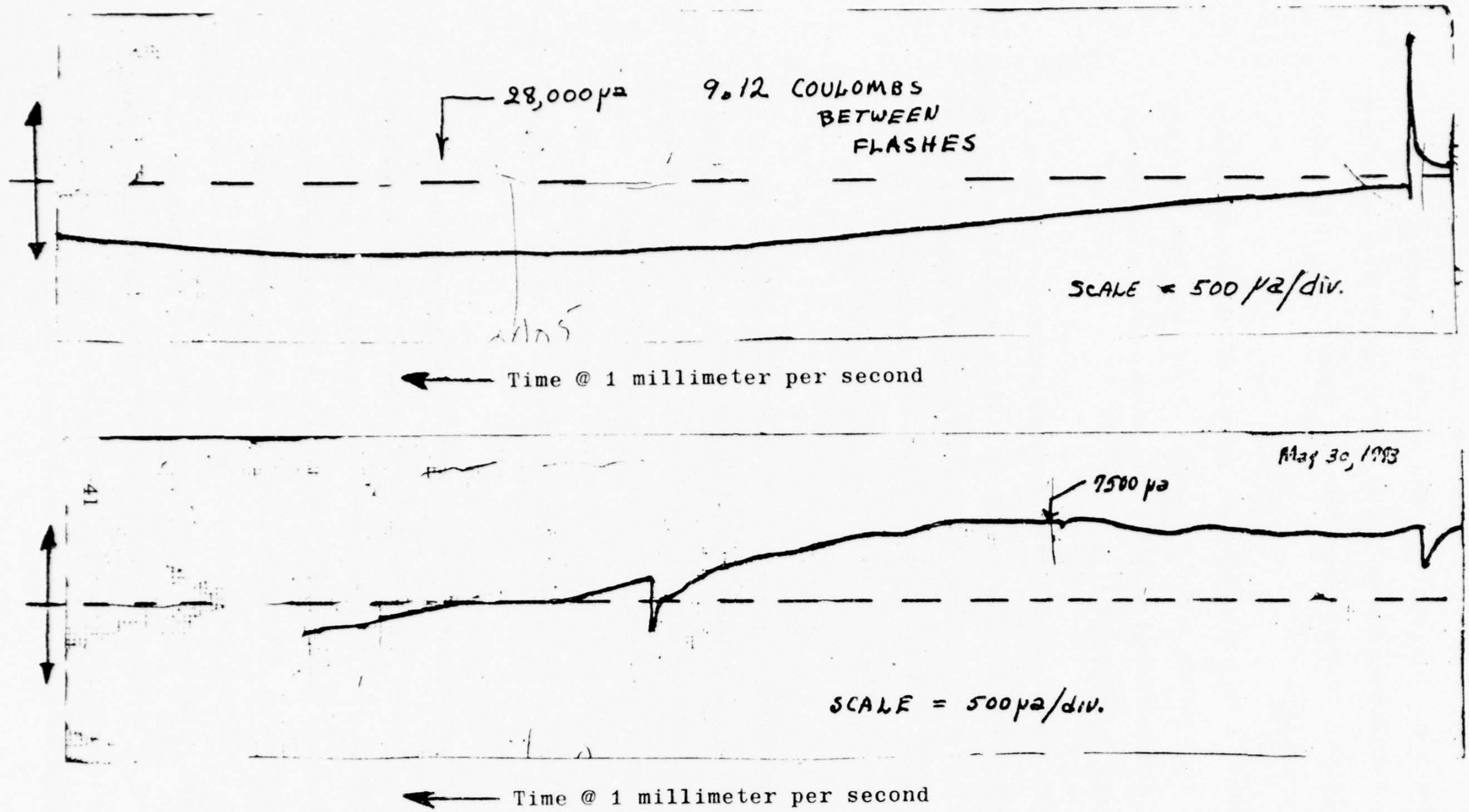


FIGURE 21. ARRAY DISSIPATION CURRENT SEGMENTS, MAY 30, 1973 (as reported in reference 16)

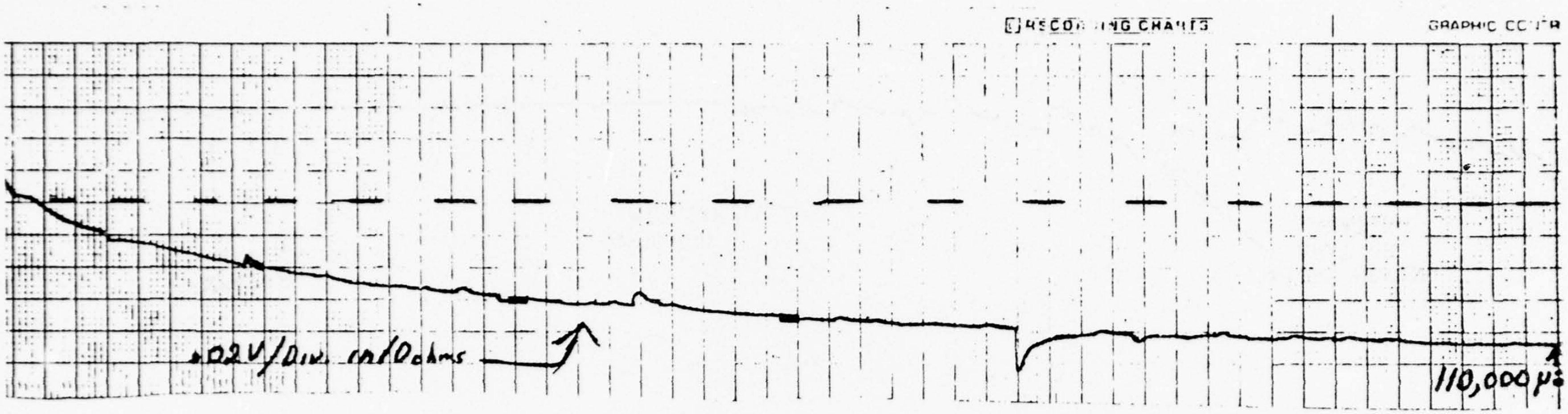
Figure 22, also from reference 16, indicates a surprisingly large peak value of 110,000 μA even though the markings of .02 V/division and 10 ohms would indicate a current of 44,000 μA. Once more, time appears to be going the wrong way.

The Rosman data is very questionable, especially in view of a Telex report from the station stating that the corona current data was severely degraded by other currents induced in the line as was noted when certain switches were thrown in unrelated lines.

Figure 23 shows the recorded corona current (reference 25) from a panel array at Rosman under a local storm saturating at a very large value of 600 μA. As the storm moves away the corona current increases for a surprisingly long period of time and lightning is reported to occur at precisely 45 minute intervals which is obviously interference from a time source.

Figure 24 is a reduction to one graph of corona data (reference 25) from an array taken over an 8 day period. The corona current remained at a very high value for almost the whole period of time implying a severe overhead storm lasting continuously for many days. This cannot be so and it must be concluded that there was pick up in the recording lines as had been shown by NASA investigations and that these results do not represent corona current.

A considerable portion of data from the MILA tracking site was examined. Many of the original data charts were obtained and were analyzed independently and then correlated with the previous results reported in reference 23. In all cases the new data reduction in no way matched the previously published results. The differences were of the order of 10^3 and the curves did not bear any similarity in polarity or movement. One such example is shown in Figure 25 where the solid line is for the new reduction and implies an acceptable value of 22 μA from the umbrella array, although the polarity is surprising and may be due to line pick up effects. The dotted line is taken from reference 23 and shows a completely different



← Time @ 1 millimeter per second

Figure 22. Corona current from 1200 foot tower dissipation array as reported in reference 16

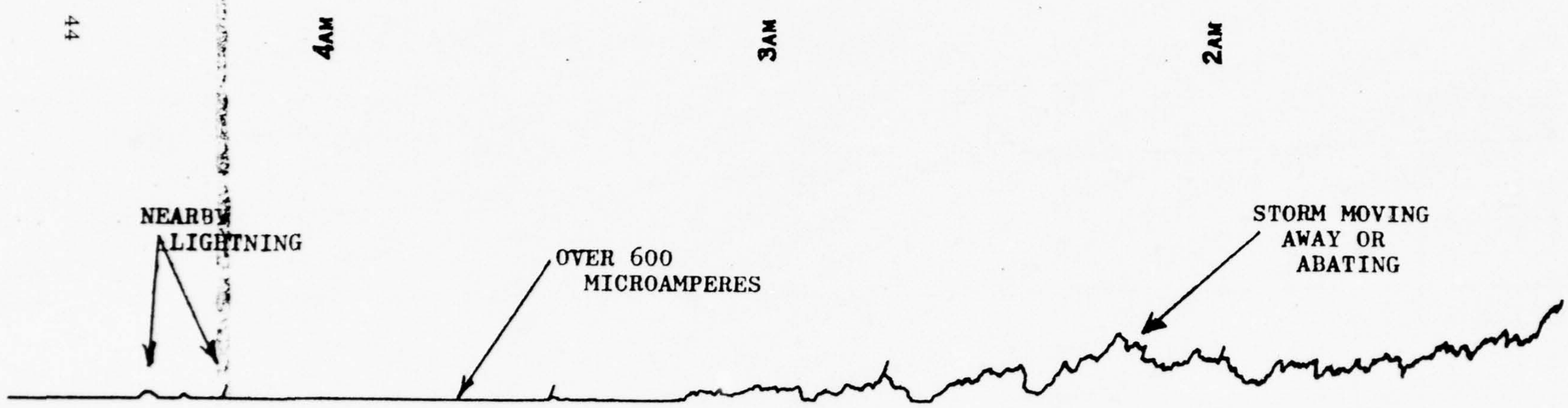


FIGURE 23 . OVERHEAD STORM, PANEL ARRAY CURRENT, MAY 20, 1974
(from reference 25)

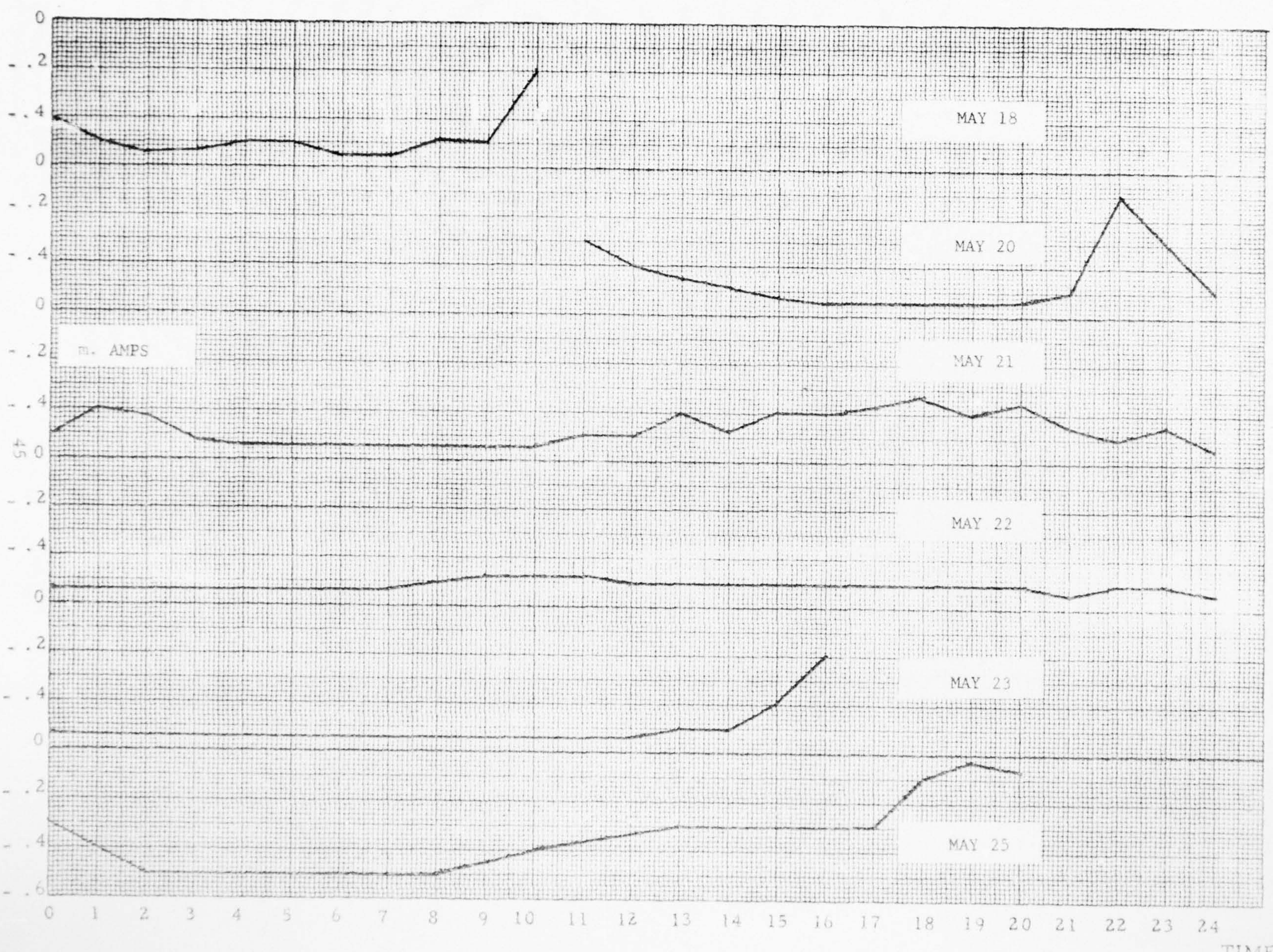


Figure 24. Rosman panel array corona current from reference 25

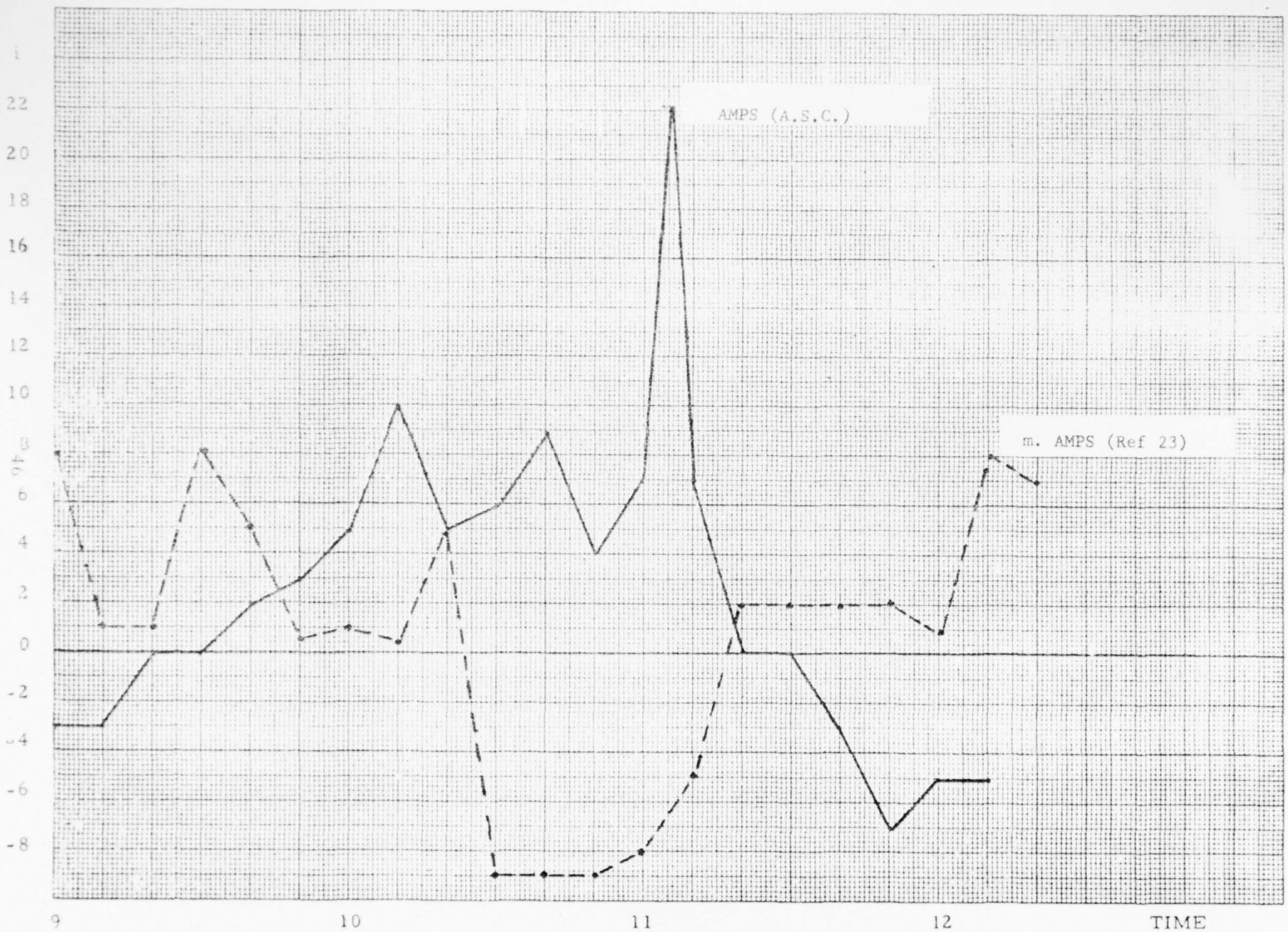


Figure 25. Comparison of MILA corona current from reference 23 and reduced by A.S.C.

curve some 10^3 times larger. Clearly there has been an earlier gross misunderstanding of the recorded data. The calibration that was used in the new reduction was taken just prior to the data being recorded.

Figure 26 shows data from reference 23 during a storm on 25 July 1975. The corona current recordings from three different arrays at the same site show extremely large values and questionable polarities. The panel array reaches a peak of 2.25 mA, the building array a peak of 67mA some 1 hour later and the umbrella array is almost consistently -175mA, except it goes very low when the other arrays peak. It does not seem possible that two arrays a few thousand feet apart can give very high opposite polarity corona current for at least six hours. The results are obviously severely degraded and cannot be accepted by the scientific community.

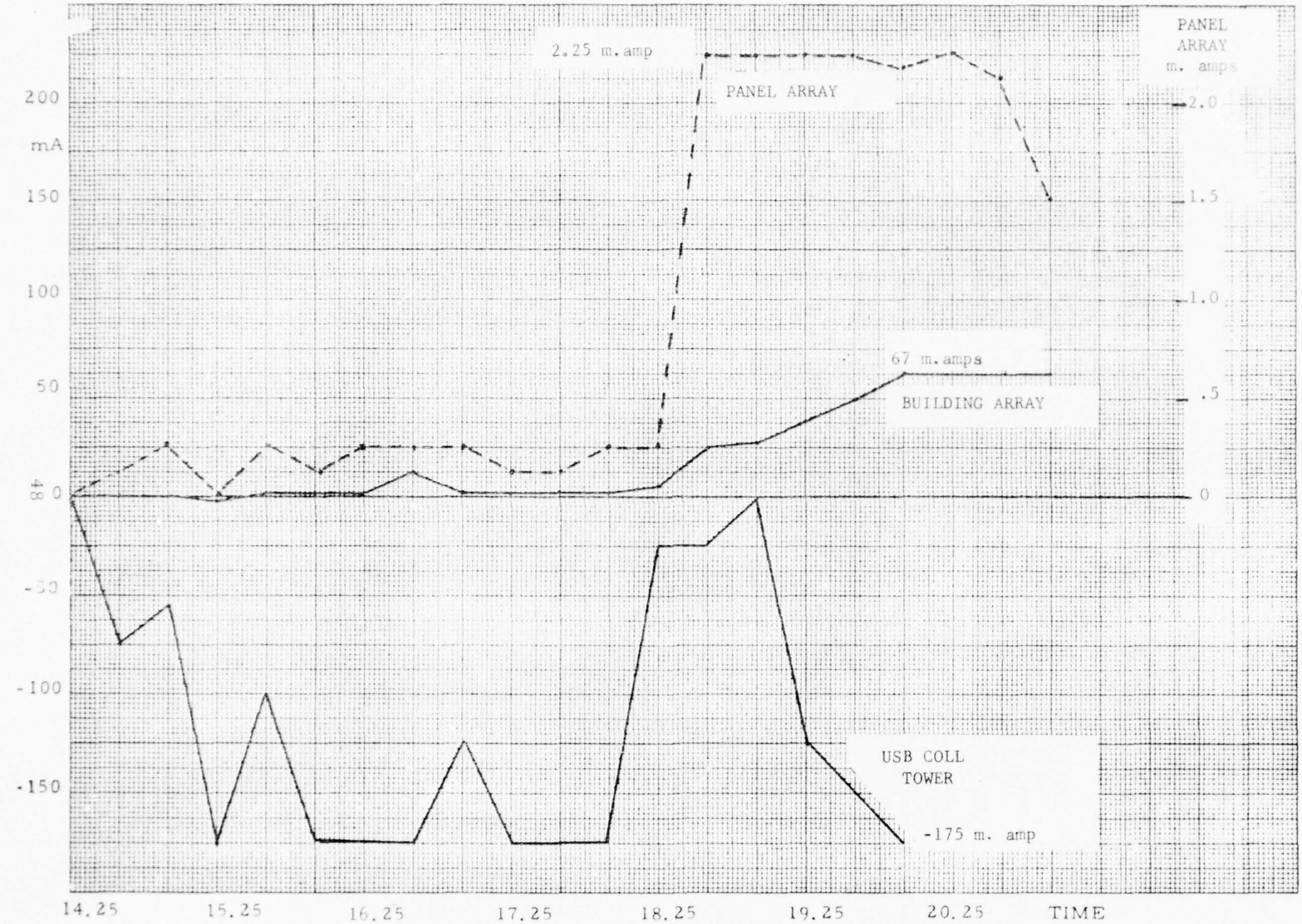


Figure 26. Corona current 25 July 1975 MILA (as reported in reference 23)

6.0 DISSIPATION ARRAY AND CORONA CURRENT INVESTIGATICNS BELOW 100 FEET AT NASA/MILA

6.1 Site Description

The measurement of corona current from an umbrella type dissipation array and from an assortment of single and multiple points took place at the NASA/GSFC Merritt Island Launch Aquisition tracking facility at Kennedy Space Center, Florida. The NASA staff under the direction of Mr. J. Dowling provided considerable assistance and equipment for the duration of the project. This site was chosen for the investigation because a variety of dissipation arrays of the types discussed earlier were already installed at the facility. Other advantages were its location in an active thunderstorm zone and the fact that comprehensive analysis of results from these arrays had already been received by NASA[23] and were utilized here for correlation purposes.

An aerial photograph of the site is shown in Figure 27. The facility housed a selection of dissipation arrays which were installed during 1974 to provide a lightning prevention system for the complete facility even though there was no evidence that lightning had ever struck it. The dissipation arrays included a 24 sq. ft panel array located between two 30 foot parabolic dish antennas, a perimeter array around the roof line of the main building, a truncated conic array on a 100 ft collimation tower and a large umbrella array over 20 feet in diameter which was located on the 100 foot collimation tower some $\frac{1}{2}$ mile north of the main facility. This distant collimation tower is shown in the upper right hand section of Figure 27 and most of the investigations were conducted there.

The area is free from man made charge generation, and the vegetation is primarily cabbage palms and palmetto which may easily give rise to natural corona because of their sharp pointed leaves.[9]

A closer view of the collimation tower complete with umbrella array is shown in Figure 28a, a close up of the array in Figure 15.

Figure 27. Aerial view of the NASA/MILA tracking site

The building at the base of the tower housed an 8 channel Brush Recorder (Fig 28b). Also visible in Figures 28a and c are 3 tripods which were used for corona current and field mill investigations. These tripods were each 20 feet tall and were separated by a distance large enough that they would not normally electrostatically interfere with one another. Field mills were located atop the 5 ft and 20 ft tripods, and the other two tripods were used for corona current investigations.

6.2 Instrumentation

Field mills were erected at 4 heights: 100 feet (Fig 15), 20 feet and 5 feet (Fig 28c) and at ground level. Corona measurements were carried out at 100 feet from the dissipation array and at 20 feet from two different sources. Wind speed and direction were also monitored halfway up the tower at 50 feet (Fig 28a).

The field mills were installed to investigate the space charge existing during thunderstorm conditions between the heights 0-5, 5-20, 20-100 feet. This data is useful in determining the amount of natural corona discharge emitted from nearby natural sources. The mills were all mounted in an upward direction and had large enough separations between the collectors and ground that they were unaffected by rain. The wind speed anemometer was adjusted to give full scale deflection on the recorder for wind speeds of either 0-25 or 0-100 mph. The wind direction was plotted automatically on an adjacent channel. Corona discharge was measured by passing the conducting cable from each of the three corona sources through separate 100 ohm 1% resistors to a common ground source. The voltage across the resistors was measured with Hewlett Packard 413A DC Null Voltmeters which are capable of measuring $\pm$ 1mV full scale and amplifying to give a $\pm$ 1V extremely stable output on the Brush Recorder. With this approach corona currents as low as $\pm 0.2\mu A$ can be measured. The use of common ground enables accurate comparison of corona current from different points.

Preliminary investigations at the site uncovered a possible problem with the earlier measurements of corona current from the dissipation array.

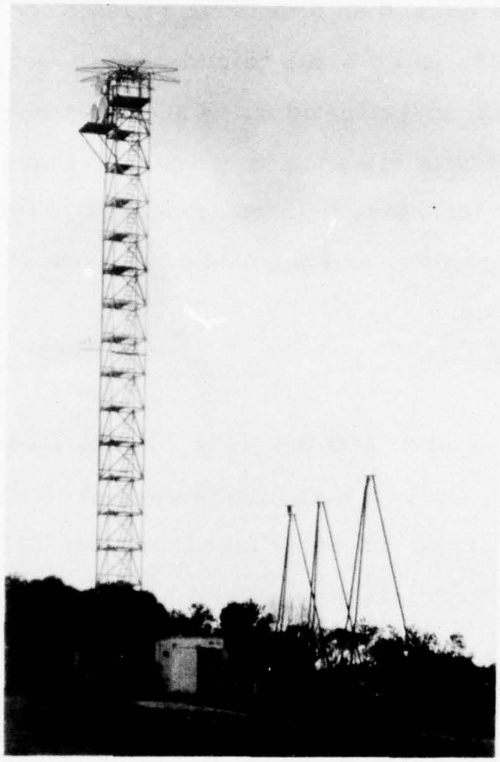


Figure 28 a.

100 foot collimation tower and three 20 ft tripods used in the investigation

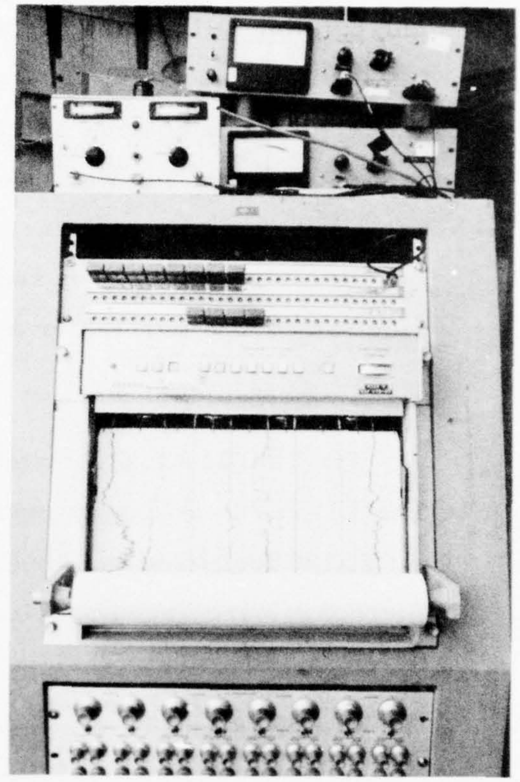


Figure 28 b.

8 channel Brush recorder used in the investigation

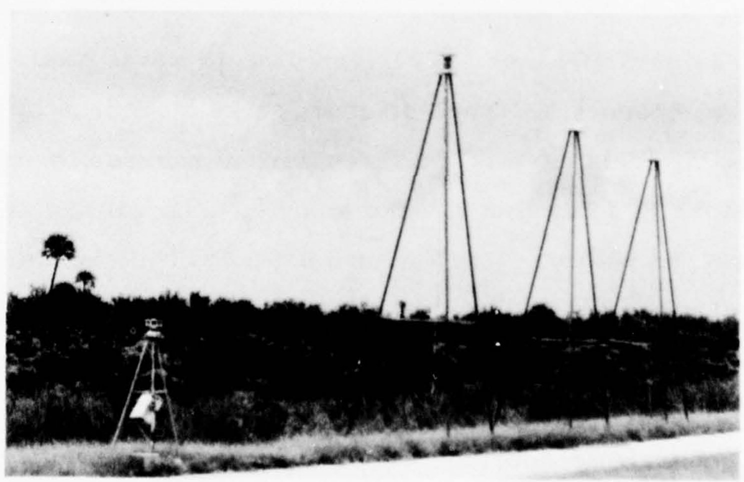


Figure 28 c.

Three 20 foot and one 5 foot tripods housing field mills and corona points

The array had a resistance of 1000 ohms to the tower as the insulation at the top had broken down. The array ground was a different ground to the tower and ground currents of several tens of microamps could be measured. If these currents had been in existence for some time they could have influenced the earlier measurements as presented in the report to NASA(23). The earlier measurements could also have been influenced by pickup in the $\frac{3}{4}$ mile cable feeding data back to the main site.

During the period of the experiment the corona points on top of two of the tripods were often changed. There were four types of points: a 2 foot $\frac{1}{2}$ " copper rod tapered off to a needle sharp point, a $\frac{1}{2}$ inch diameter point, a 14 inch length of dissipation wire containing 16 barbs and an 8 foot piece of dissipation wire looped in a $2\frac{1}{2}$ foot diameter circle.

The recorder was an 8 channel Brush analogue pen recorder with chart speeds varying from .05 to 200 mm/sec which allowed excellent correlation of data.

6.3 Results

Consider the corona current from the extremely large dissipation array which contains approximately 1000 feet of "dissipation wire". During the summer of 1975 the maximum corona current measured from the array at 100 feet was only 38 μA. This value is in keeping with the currents measured throughout the years and reported by Chalmers(6). At no time was there any indication that the array was performing any differently from a single point. Extremely large displacement currents were often recorded, as one might expect, and are not to be confused with corona currents. Such excursions are shown in Figure 29 superimposed on genuine corona currents of 0-20 μA. This figure shows the onset and decline of a short lived storm and also displays the potential gradient at ground level on which the lightning discharges and field buildup can be seen.

The behavior of a large umbrella array under high field conditions is no doubt very complex. One might consider that the field close to the

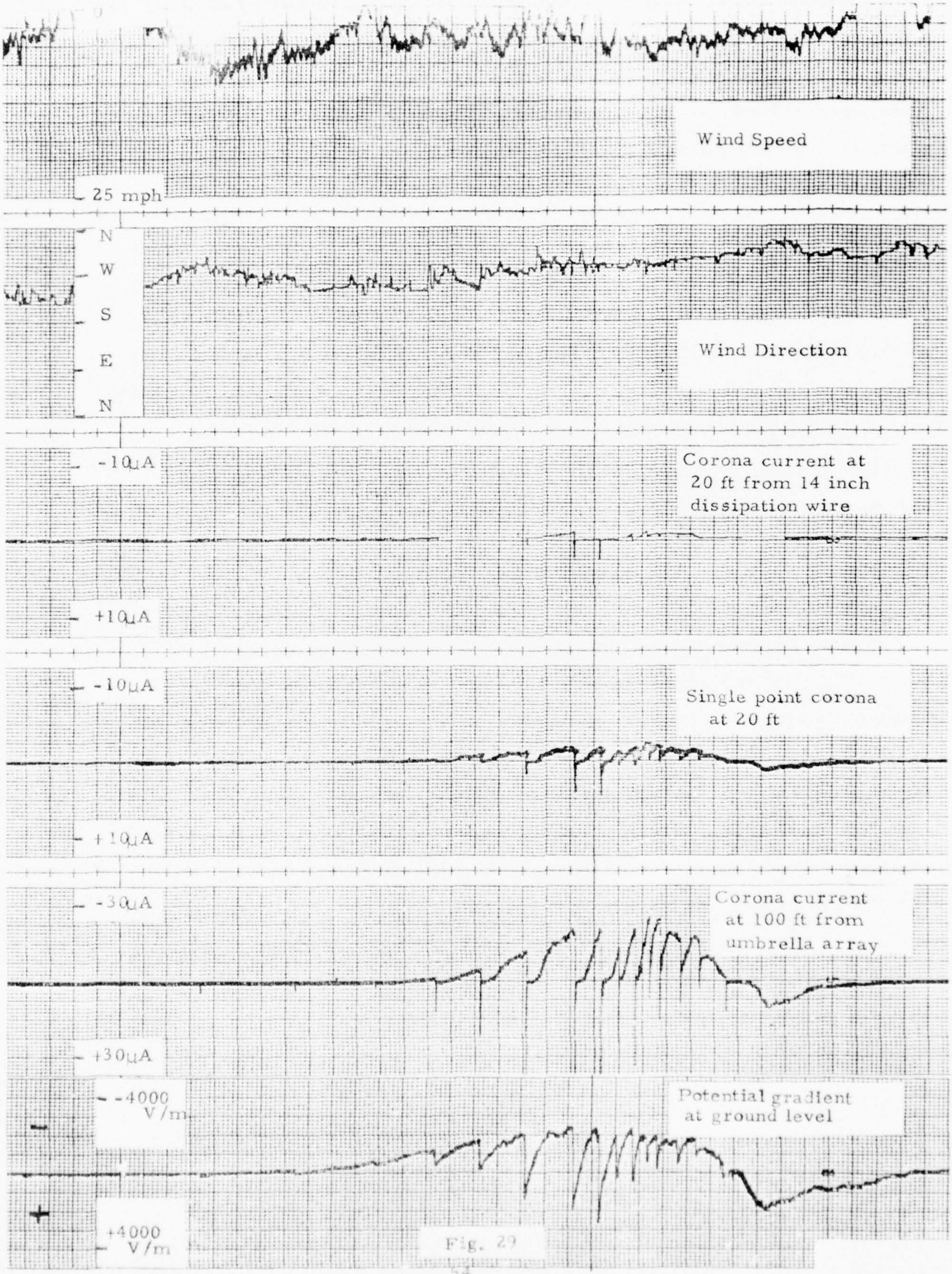

0
Wind Speed
25 mph
N
W
S
E
N
Wind Direction
-10μA
Corona current at
20 ft from 14 inch
dissipation wire
+10μA
-10μA
Single point corona
at 20 ft
+10μA
-30μA
Corona current
at 100 ft from
umbrella array
+30μA
-4000
V/m
Potential gradient
at ground level
−
+
+4000
V/m

Fig. 29

edges of the array will be very large but earlier discussions have shown that on top of the slightly spherical structure the field will be enhanced only by a factor of about 3. Corona will initially be given off from the perimeter of the array where high fields exist and this corona will probably be blown by the wind over the rest of the structure thereby reducing the field more, and lowering the possibility for corona discharge. Hence, only a small portion of the array may give rise to prolonged and high corona.

Simultaneous with the corona discharge measurements from the dissipation array, Figure 29 compares corona from a single point with that from 14 inches of the same type of dissipation wire. This wire was comprised of 4 groups of four 2 cm long barbs. The results indicate that the single sharp point gives off approximately 50 percent more corona than the multiple point, which in turn gives off about $\frac{1}{10}$ that of the dissipation array located at an elevation 5 times as high.

One may now argue that if 14 inches of dissipation wire emits $\frac{2}{3}$ of the corona from a single sharp point then 21 inches would emit the identical amount and 42 inches would emit twice as much. Even if one doesn't expect a linear relationship it may be expected that longer lengths will emit more corona. In order to test this hypothesis an 8 foot piece of dissipating wire was wrapped in a $2\frac{1}{2}$ foot circle and placed on a tripod at 20 feet for comparison with corona from a single point. With the large circular configuration of the wire a higher field will exist around it than would be the case if it were spirally wrapped as in the umbrella array. The higher field would lead to more corona discharge.

Figure 30 shows some typical results of comparisons of data between the umbrella array at 100 feet, and the single point and 8 feet of dissipation wire at 20 feet. The umbrella array reaches currents of $35\mu A$, which once more are about ten times greater than the values for the lower altitude single point. In this example the single point gives off approximately 50% more corona than the long length of dissipation wire. The maximum sustained currents were the order of $3\mu A$ from the single point and $2\mu A$ from the wire.

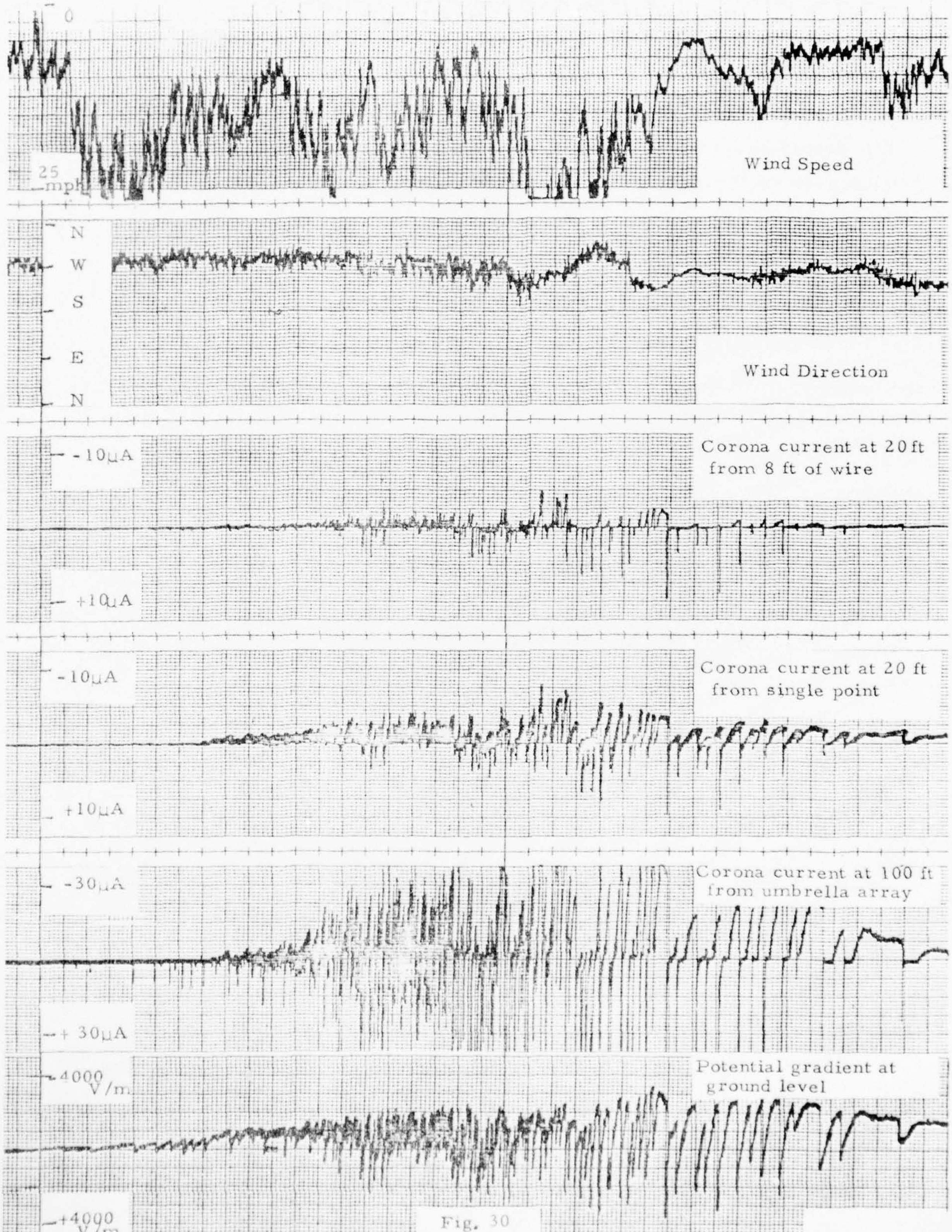

0
25
mph
Wind Speed
N
W
S
E
N
Wind Direction
-10μA
+10μA
Corona current at 20 ft
from 8 ft of wire
-10μA
+10μA
Corona current at 20 ft
from single point
-30μA
+30μA
Corona current at 100 ft
from umbrella array
-4000
V/m
+4000
V/m
Potential gradient at
ground level

Fig. 30

The potential gradient during this time reached a value of -3000 V/m at the earth's surface and there was considerable lightning activity as evidenced by the large number of displacement current excursions. The single point, by virtue of its sharpness and elevation gave off corona of the order of $\frac{1}{10}$ to $\frac{1}{4}$ μA under fair weather fields of about +100 V/m, whereas the umbrella array needed breakdown field of $\pm$ 1100 V/m and the 8 feet of dissipation wire needed fields in excess of $\pm$ 2000 V/m for breakdown at the much lower altitude. At no time was there any indication that the 8 feet of corona wire gave off more corona than the single point.

Under high field and high wind conditions there were two occasions when the single point and the 8 feet of wire gave off similar amounts of corona. Such an example is shown in Figure 31. One can also see that the breakdown point occurs at a much lower potential gradient for the single point than the multiple point. The effect of the breakdown potential is more noticeable in Figure 32 where the field remains at a level just below that required for the 8 foot of dissipation wire to go into corona discharge.

The 14 inch piece of dissipation wire also on one occasion gave corona currents similar to the single point. Again, this was under high field and high wind conditions as displayed in Figure 33. Throughout the summer thunderstorm season there was no occasion when the single point gave off less corona than a multiple point at the same height. In general the 14" and 96" dissipation wires gave off similar amounts of corona at levels approximately $\frac{1}{3}$ less than the single point.

Once more, the maximum corona current measured from the umbrella array was under 40 μA. The single point at a much lower altitude gave a maximum value of about 5 μA. These values are in keeping with the many investigations of corona current taken in the past by many scientists as referenced earlier.

The $\frac{1}{2}$ inch blunt point never went into corona which was visible on the chart moving at about 6 inches per hour. Displacement currents were

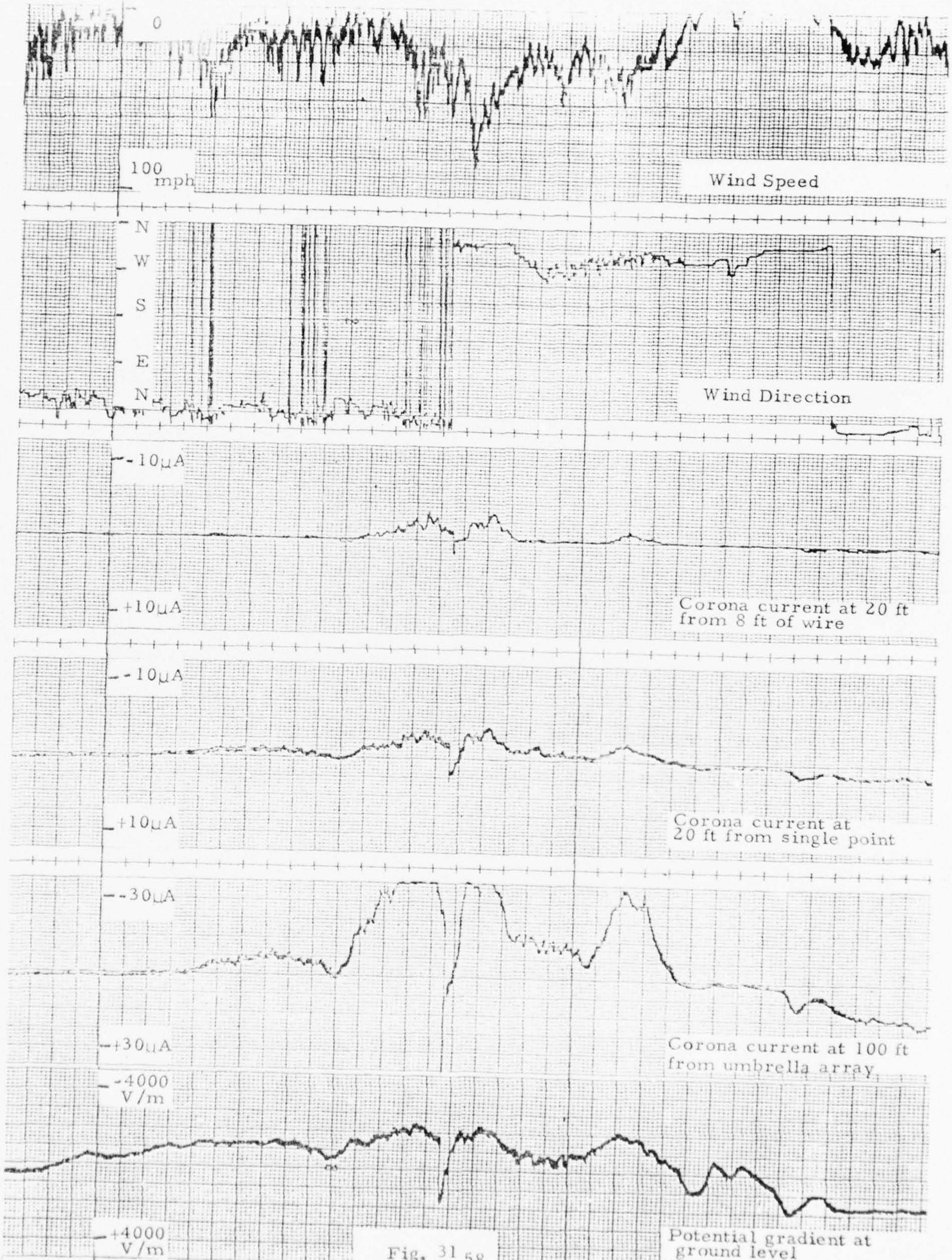

0
100 mph
Wind Speed
N
W
S
E
N
Wind Direction
-10µA
+10µA
Corona current at 20 ft from 8 ft of wire
-10µA
+10µA
Corona current at 20 ft from single point
-30µA
+30µA
Corona current at 100 ft from umbrella array
-4000 V/m
+4000 V/m
Potential gradient at ground level

Fig. 31

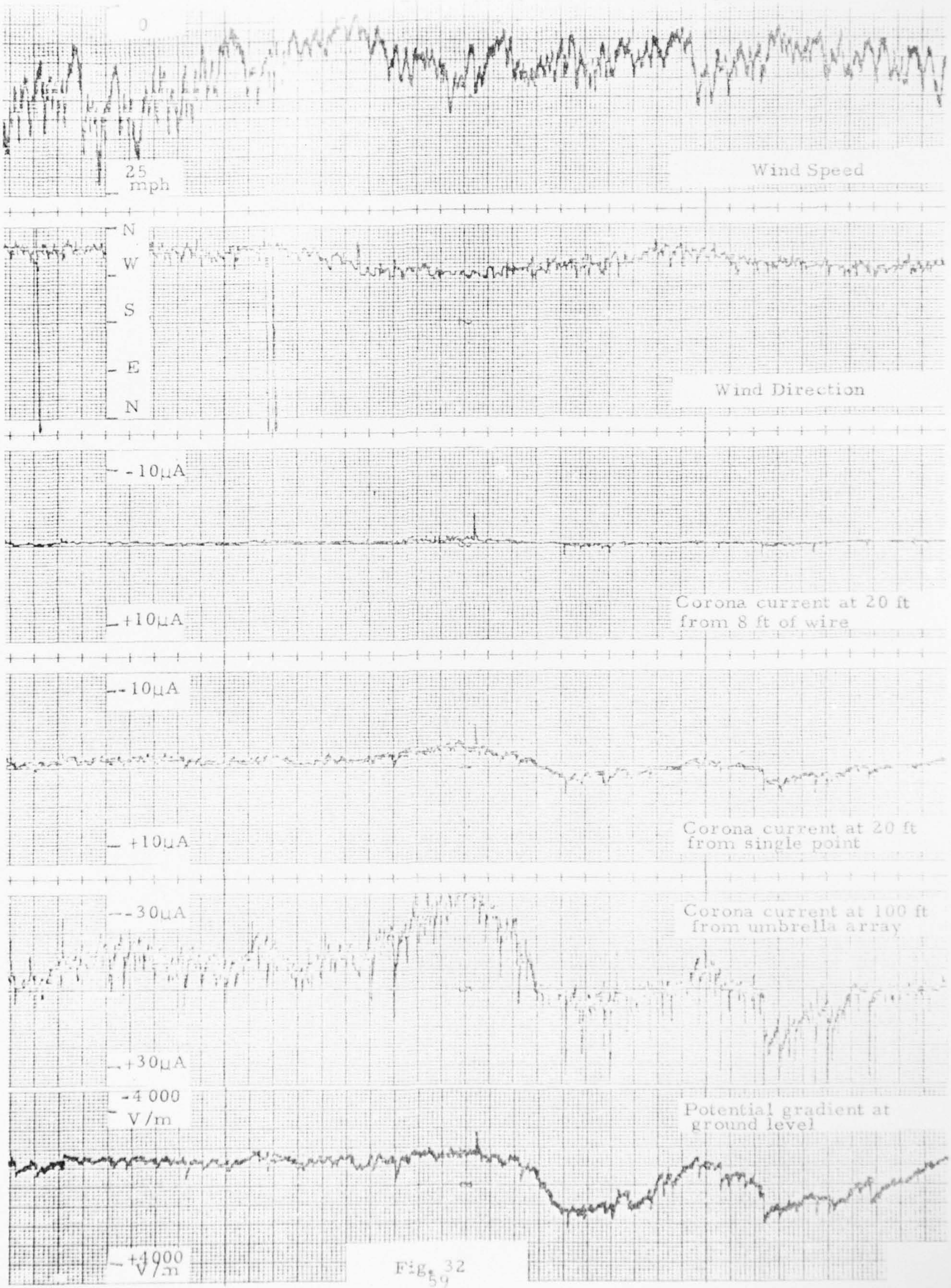

0
25 mph
Wind Speed
N
W
S
E
N
Wind Direction
-10µA
+10µA
Corona current at 20 ft from 8 ft of wire
-10µA
+10µA
Corona current at 20 ft from single point
-30µA
Corona current at 100 ft from unbrella array
+30µA
-4 000 V/m
Potential gradient at ground level
+4000 V/m

Fig. 32

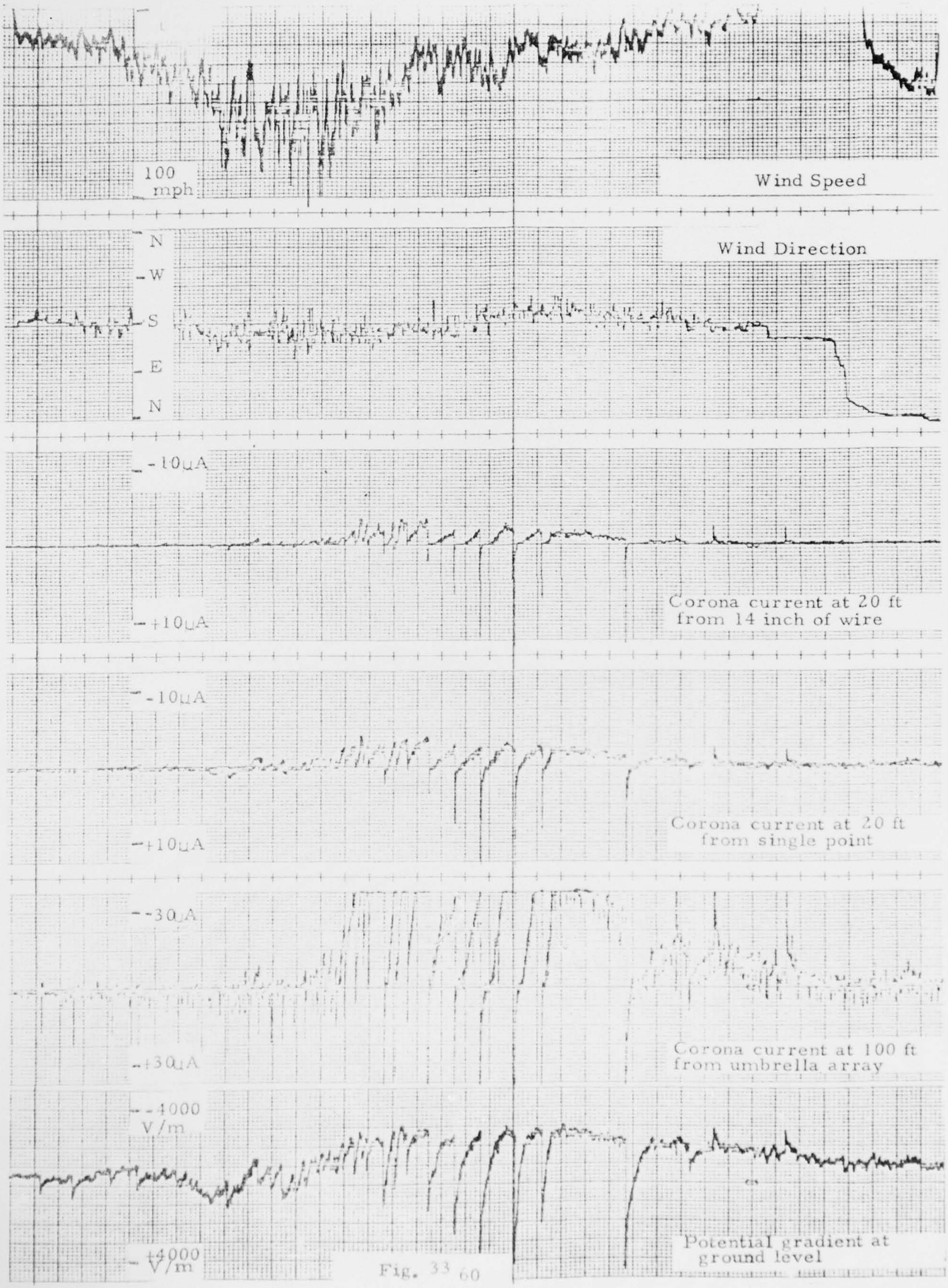

100 mph
Wind Speed
N
W
S
E
N
Wind Direction
-10μA
+10μA
Corona current at 20 ft from 14 inch of wire
-10μA
+10μA
Corona current at 20 ft from single point
-30μA
+30μA
Corona current at 100 ft from umbrella array
-4000 V/m
+4000 V/m
Potential gradient at ground level

Fig. 33

obviously visible and there may be a possibility that occasional sudden extremely high values of electric field may have given rise to corona from this blunt point, but the chart speed used for most of the data did not allow such observations.

The results certainly contradict the reports that many milliamperes of corona current is emitted from these arrays. One point that could not easily be confirmed at this site however was that a single point gave off more corona current than a dissipation array at the same height. Fortunately, such an array and two 50 foot wooden poles for comparison test were provided at another site. The array was a circular panel array approximately 6 feet in diameter. This array was placed atop a 50 foot wooden pole and connected to ground through a 10 ohm 1% resistor. Another 50 foot wooden pole some 300 feet away housed a single sharp copper point identical to a lightning rod air terminal and connected to the common ground through a separate 10 ohm 1% resistor. The voltage across these resistors was monitored on a Honeywell Visicorder along with wind speed and direction. The results again agreed with scientifically accepted belief. At no time did the corona from the flat panel dissipation array exceed that of the single point.

Figure 34 illustrates the largest currents that were recorded at both the array and the single air terminal. The thickness of the basic trace on the array record is due to 60 cycle pickup and the large sudden excursions are due to displacement currents when lightning occurs. When the wind speed increases and large currents are flowing, then a further increase in the corona current is evident. In this case the wind direction is such as to cause no space charge interference between the two instrumented poles. At the beginning of the record a severe storm is in progress with many discharges, but the corona current from the array does not exceed 6 μA. As time progresses the displacement currents get somewhat smaller as the lightning becomes more distant, but the field increases as a new charged cell passes overhead. It appears that three lightning discharges

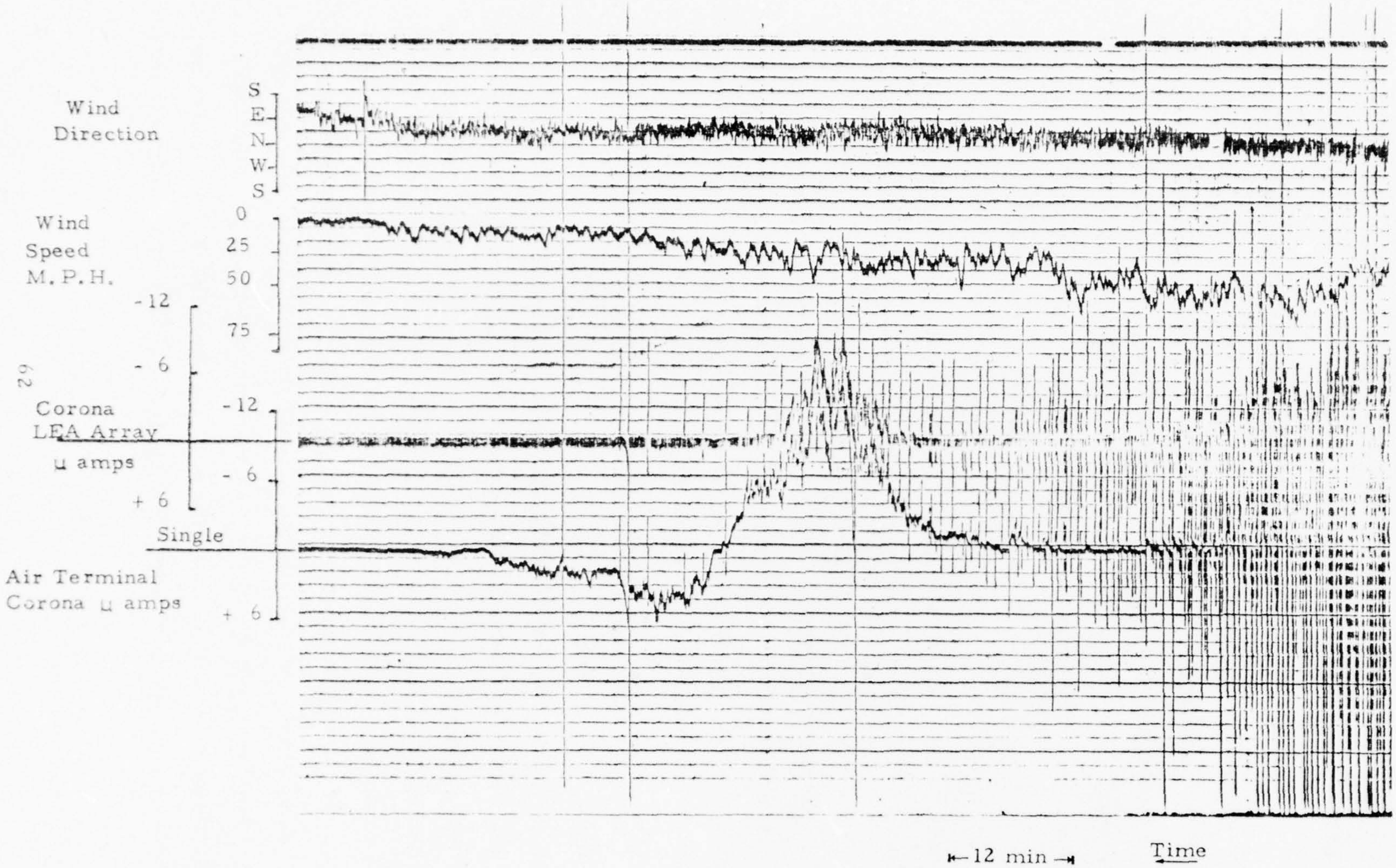


Figure 34. Corona Current Results from LEA Array and Single Air Terminal

resulted from this cell and caused three very large displacement currents. In these high fields the air terminal current yields up to 14.5 μA; whereas the array current only reached 8.5 μA. The array only went into corona when the air terminal was dissipating 6 μA. After this the rate of increase of the array current was the same as the air terminal. This means the array is unlikely to give more corona than the air terminal, even in the extremely high fields of the downward coming leader. Further results at this facility demonstrated similar effects.

NASA/KSC personnel also measured the corona current from a panel type dissipation array on top of a 500 foot tower at KSC and found that the value throughout the summer thunderstorm season remained below 200 μA. This array was also struck by lightning (Fig 13).

It must thus be concluded once more, that a single point gives more corona discharge than a multiple point and more than the dissipation arrays under test. *A single point is, therefore, a much* better dissipator of ions and if one must believe in cloud charge dissipation or a protective ion cloud, then a single point should be the main dissipator and not multiple points. A further striking but not unexpected conclusion is that natural corona from the nearby vegetation as measured by field mill space charge techniques between 0 and 100 feet, was found to be an average 1 μA per tree under severe thunderclouds. It may, therefore, be concluded that the 30 or so palm trees cleared for the construction of the 100 foot collimation tower would emit the same corona current as the 1000 feet of dissipation wire placed at the top of the tower.

7.0 PHOTOGRAPHIC AND CORONA INVESTIGATIONS OF AN ARRAY ON A 1200 FOOT TOWER AT EGLIN AFB

7.1 Site Description

Site C9, Eglin Air Force Base, Florida was chosen for this investigation because it houses a 1200 foot tower which should be struck by lightning more than 40 times per year (see Section 4.0). The tower also supported a 19 foot diameter umbrella type dissipation array which was replaced in April 1974 with three 6 feet x 4 feet panel arrays placed parallel with the ground and some dissipation wire at the edges of the panel on a framework making an angle downward from the array.

Figure 35a is a photograph of the 1200 foot tower; Figure 35b shows a view of the panel arrays. Close examination shows the dissipation wire at the edge of the array. Figure 35c is a downward view of the panel array showing the sharp 4 cm spikes.

7.2 Instrumentation

Magnetic links were placed on the downlead from the array some 3 feet below the top and also at the bottom of the tower on the same downlead. The 3 ferrous links in each 65 cm arm were placed at 13, 26 and 62 cm from the conductor (see Figure 36). Once the links are de-gaussed a current between 5,000 and 200,000 A will cause magnetization of the links which in turn can be measured and the intensity related to the lightning current. The magnetic field strength H at a radial distance r from a long straight conductor carrying a current I is given by $H = \frac{2I}{r}$. The field effects the ferrite material and produces a magnetization of intensity $M = \chi H$, where the magnetic susceptibility χ is a function of the material. The magnetization is measured and from it the lightning current that passed through the conductor is calculated. Should there be multiple strokes only the peak value will be recorded. By placing three links at various distances in each arm more accurate measurement of current are allowed as the magnetic intensity is a function of distance from the conductor.

The positioning of the two arms was not ideal for monitoring current

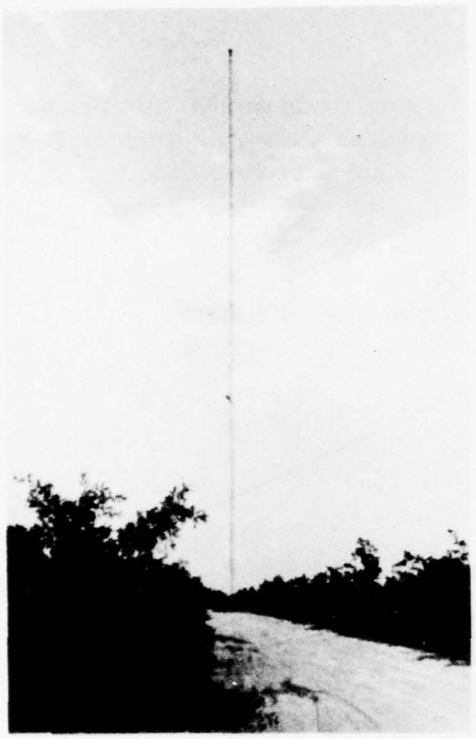


Figure 35 a.

1200 foot tower, Eglin A. F. B. Florida site C9

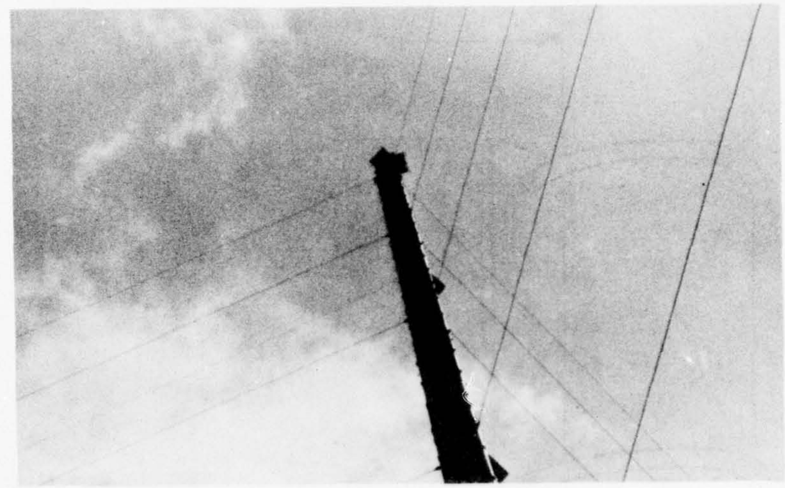


Figure 35 b. *View of the top of the 1200 ft* tower showing the panel arrays

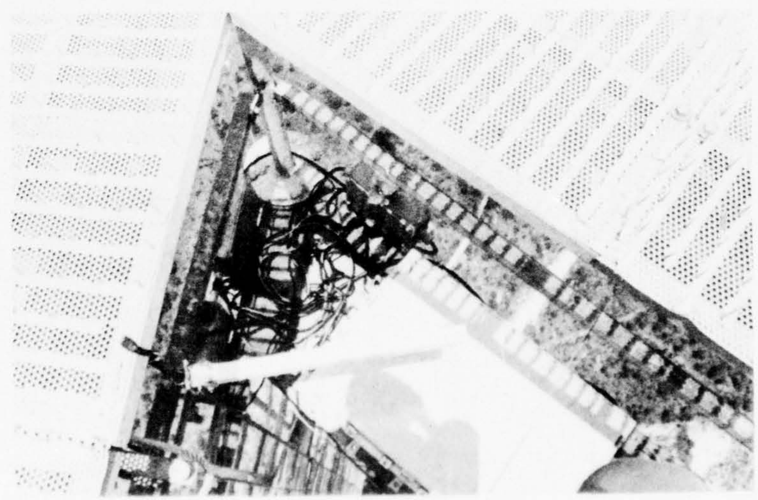
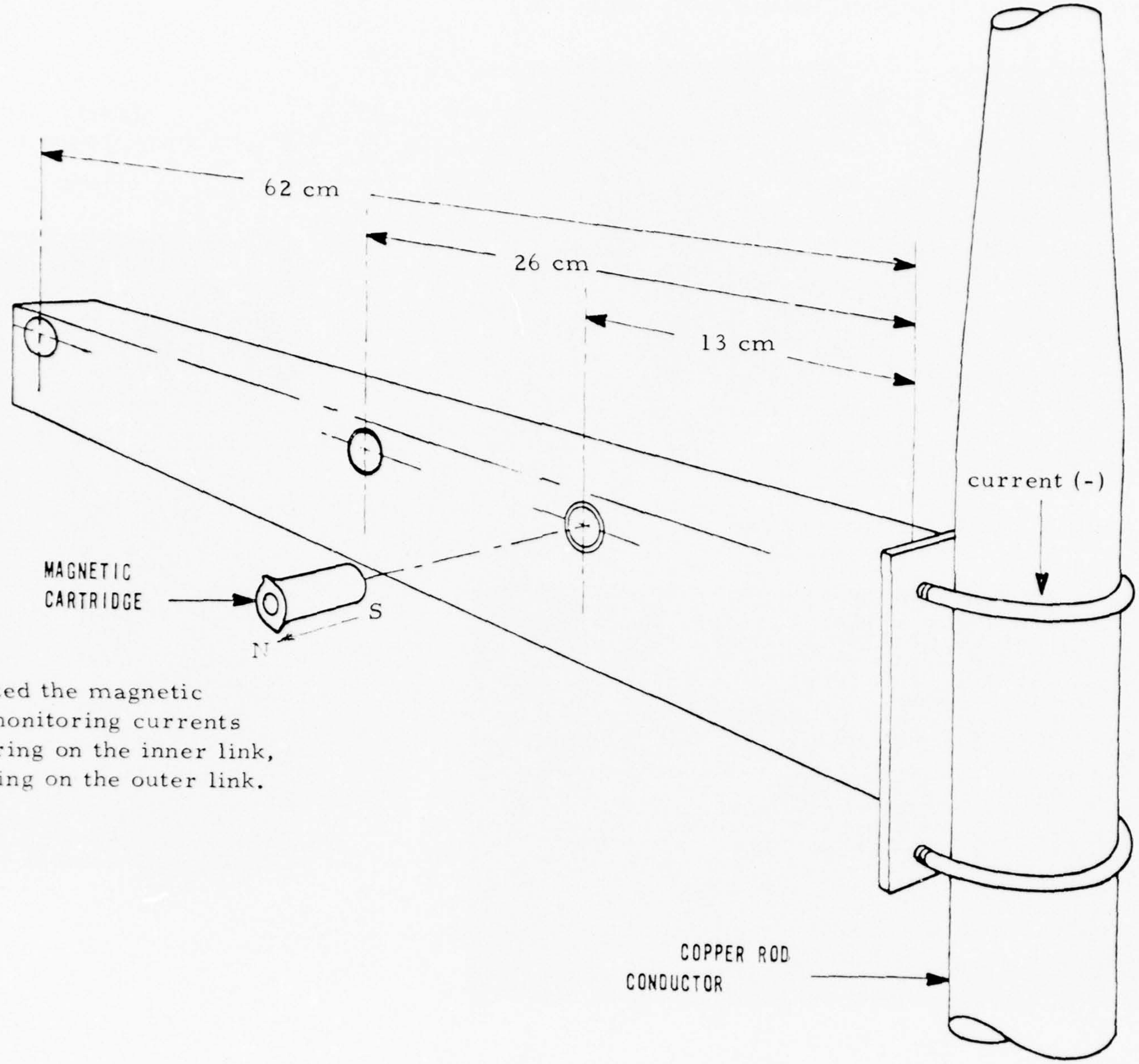


Figure 35 c. View down the middle of the 1200 ft tower showing the magnetic link arm



With distances indicated the magnetic links are capable of monitoring currents from 5,000 A registering on the inner link, to 200,000 A registering on the outer link.

Figure 36. TYPICAL MAGNETIC LINK LIGHTNING DETECTOR

from the lightning strike, as it was unlikely that the number 6 copper wire from the array would be carrying all the current if the array had been struck. In fact, most of the current would probably pass down the tower structure. The magnetic link data would, however, act as an indicator that lightning had struck and give some idea of the order of magnitude of the current. In later tests when a single lightning rod was put up, it would give accurate measurements of peak current. A magnetic link arm is shown in photograph 35c.

At the base of the tower the array was grounded through either a 10 or 100 ohm resistor to an excellent ground and the corona current monitored after amplification with a Hewlett Packard DC Null Voltmeter. An RSA-10 lightning flash counter (ref. 24) provided by FAA, NAFEC was installed near the base of the tower. The unit had a 4 m whip antenna and whenever lightning occurred within about 15 miles a signal was put on the chart recorder. This gave an indication of storm days for later correlation with lightning incidence data.

In order to examine lightning incidence to the tower, video photography was installed at a trailer some 1200 feet south of the tower at Rockhill forestry tower some 4 miles west. The video equipment incorporated silicon diode cameras, time code generators and remote control video tape recorders. Silicon diode cameras were used because they cannot be damaged by looking into the sun, they have a much wider visible spectrum than vidicon cameras and their retention capabilities are good if used in a slow motion mode. They are extremely sensitive and can be made to bloom if the source is very bright. The time code generator was modified to provide it with an external battery source. This modification was necessary because of the remote position of the site and the constant short lived breaks in the power which could modify the accurate time code information.

The silicon diode camera in the trailer was focussed on the tower through a wide angle lens with remote controlled iris that looked at the tower through a porthole in the trailer as shown at the left hand side of Figure 37a. The recording equipment is shown in Figure 37b and the position of the trailer as viewed from the tower is shown in Figure 37c. Figure 38a shows the 100 foot

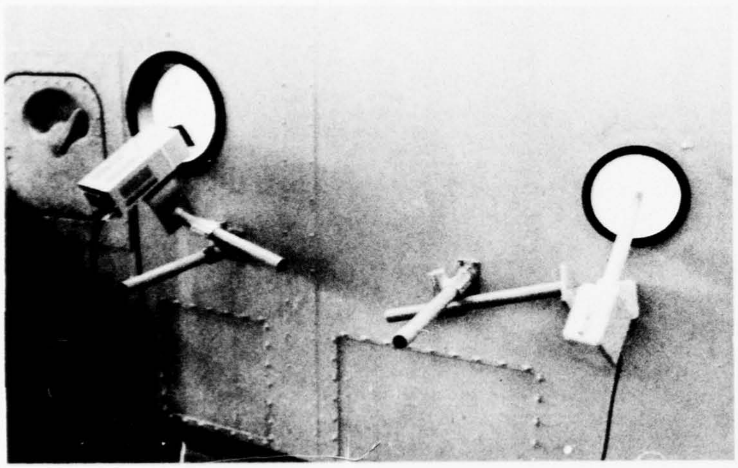


Figure 37 a.

Silicon diode video camera and lightning transient detector in the trailer at site C9, Eglin A.F.B. looking at the 1200 ft tower

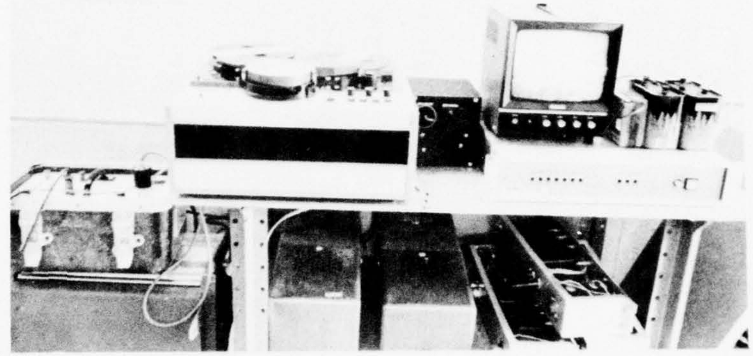


Figure 37 b. Recording equipment installed in the trailer at site C9, Eglin A.F.B., Florida

Figure 37c. The equipment trailer viewed from the top of the 1200 ft tower

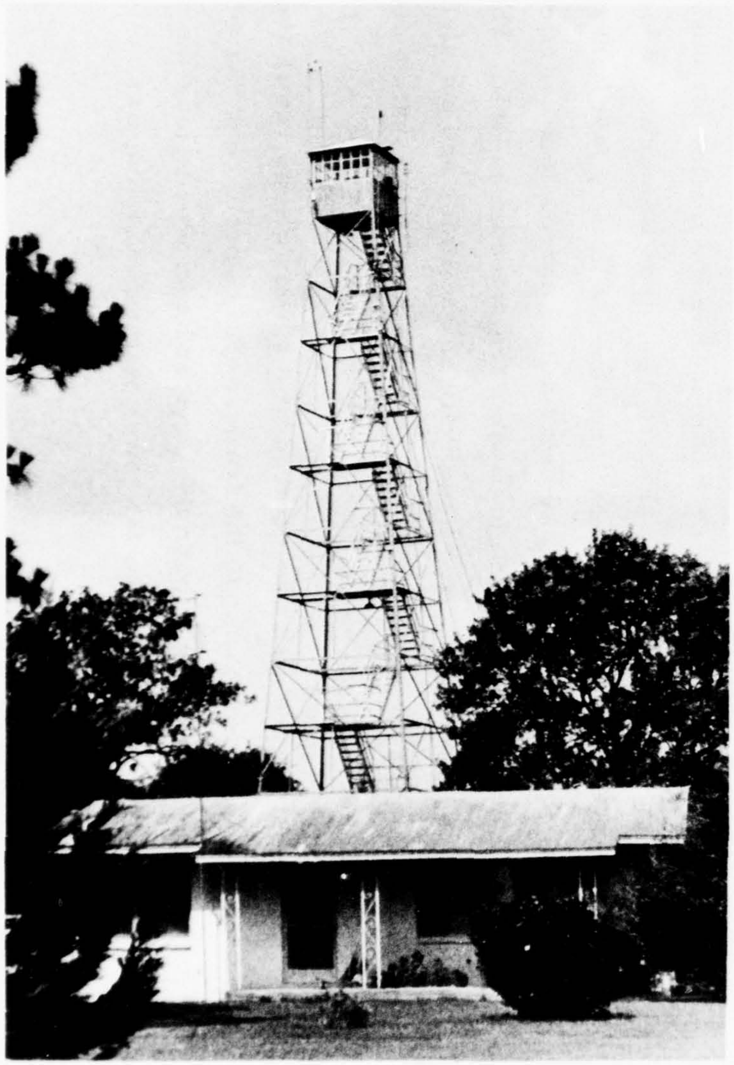


Figure 38 a. 100 ft forestry tower 4 miles west of the 1200 ft tower

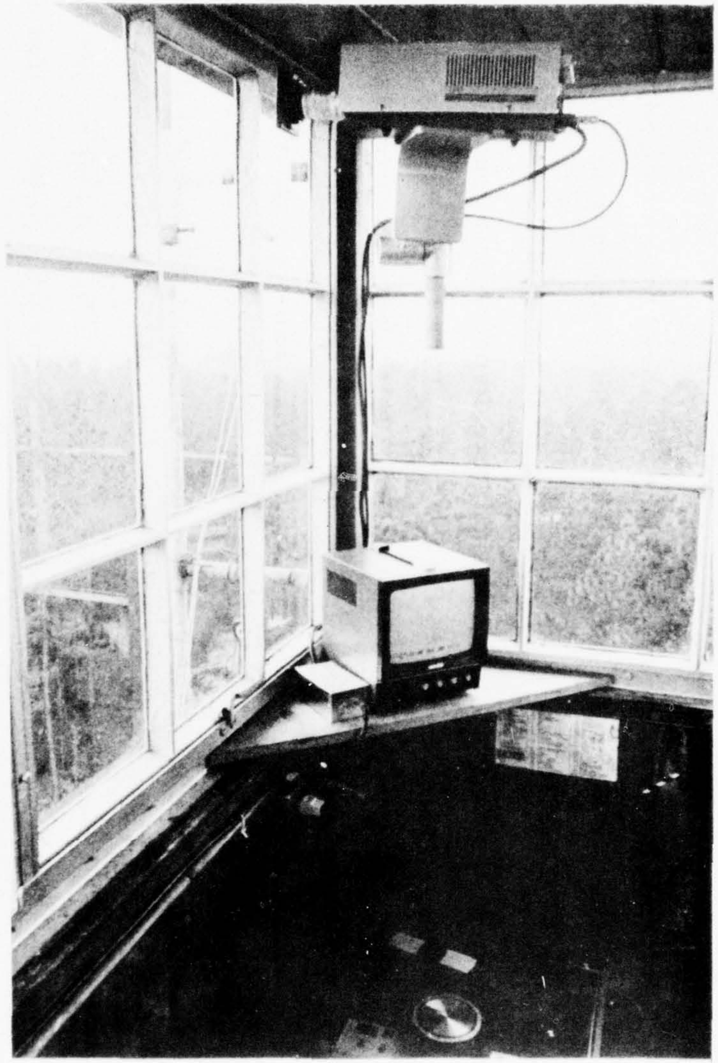
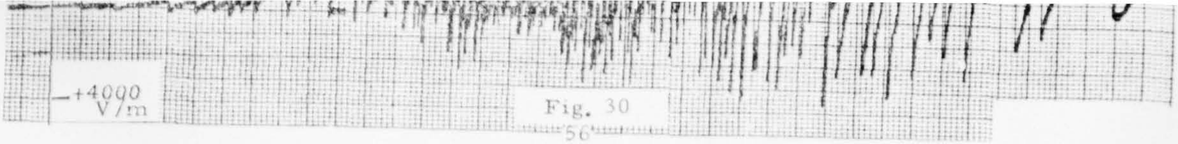


Figure 38 b. Video equipment installed in the forestry tower



Rockhill forestry tower and Figure 38b shows the video equipment in position. A telephoto lens was used in this camera to focus the image on the 1200 foot tower.

At the Rockhill tower the video equipment was turned on manually whenever storms were in the area, but at the trailer site the video equipment was turned on automatically. A microwave telephone link from the weather office at Eglin Air Force Base to the C9 tower was used to automatically switch on the video equipment whenever a storm was believed to be in the vicinity of the site. Unfortunately the equipment was often damaged at site C9 when diodes in the automatic control equipment were blown by line surges. These lines went only from the microwave antenna on the tower to a building some 30 feet away and the damage indicated that surges came in on these lines and not the power lines. It is strongly suspected that at least four outages were caused by lightning strikes to the tower effecting the automatic switch on circuitry. Because of the many malfunctions in the communication lines considerable storm activity at C9 was not recorded.

An optical lightning detector was placed in the trailer for observing discharges close to the tower top. Figure 37a shows this detector looking through the right hand porthole. The detector responds to very fast light transients and it was trained on the tower top by using a long narrow tube. Reflections of lightning from clouds in the field of view are detected as well. The data was recorded and it also was used to activate an oscillator and put a signal on the audio channel of the video recording in order to help in locating discharges on the videotape.

Problems were also encountered with surges passing down the lines running from the base of the tower to the trailer. Surge protection was added to these lines, but at times diodes were damaged and equipment stopped. These surges could only have come in from the tower as the power line was isolated and came from a different direction.

the chart moving at about 6 inches per hour. Displacement currents were

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7.3 Site Grounding

During the summer of 1975, the resistance of the tower from top section to bottom section was measured as 0.22Ω, implying that the sections of the tower were reasonably well connected to one another and that the grounded array wire did not significantly change the grounding situation at the top of the tower. It had previously been thought that if lightning struck a tower top that was not at ground potential the high current may pass through an instrument line near the tower top that would have a better ground connection, hence causing equipment damage. This could be the case if the tower was not well grounded and the instruments power ground was of lower resistance. An examination of the facts indicates that this may often have been the problem.

The original grounding system for the tower was two 20 feet by $\frac{5}{8}$ inch inter-connected copper ground rods at the tower base and one at each of the three guy bases as shown in Figure 39. The low resistance of these rods to ground in the sandy conditions of Eglin is questionable, and in order to test it, earth resistance measurements were made on a 3 inch by 10·foot copper rod a few hundred feet from the tower. During a number of months and some extremely heavy rains its resistance was measured by FAA and USAF personnel to be some 170 ohms. This implies that the resistance of the original tower ground rods was also high.

The log book however indicates that by Jan. 1972, a wire was connected from the tower ground to the 285 foot deep well some 150 feet from the tower. This well ground has been measured by FAA and USAF personnel and found to be between 1 and 3 ohms to ground which is considerably better than the copper rods. This implies that whenever the line between tower and well was damaged, lightning current would probably pass down instrument lines to power lines and other better ground connections causing havoc along the way. Prior to the stranded wire being laid to the well in 1972, the copper pipe was used as a ground and was at times found to have poor continuity due

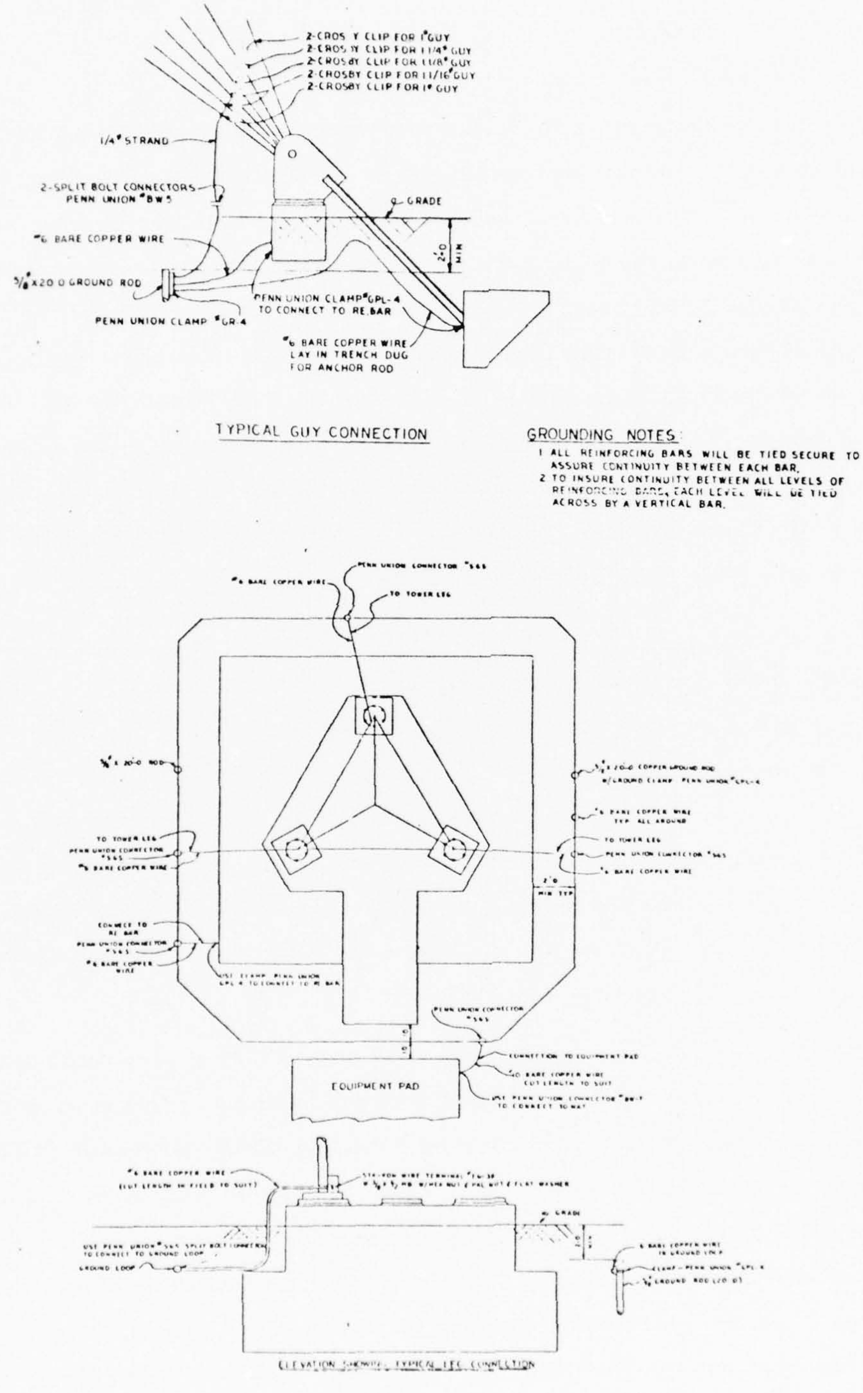

Figure 39. Original grounding of 1200 foot tower base and guys

to corrosion. On the 5 Sept. 1972, the ground network was improved by the array manufacturers and nine 6 ft x $\frac{5}{8}$ inch copper ground rods were connected to the tower and well grounds as shown in Figure 40.

7.4 Results

7.4.1 Corona Current

The initial investigations on the array showed that it had a resistance to the tower of about 3k ohms, which gave rise to "Telluric" or ground currents of the order of 150μA due to the differing ground configurations. An indication that such an effect was occurring during the corona recording period discussed in reference 16 was shown in the log book recording of 20 Dec 1972, when a resistance check gave different values with the meter leads reversed. Corona dissipation could be a reason for this, but the resistance was tested by AC and high current DC means and showed conclusively that ground loops existed. These were probably a function of power ground to the top of the tower, a poorly insulated array and the tower ground.

Prof. Olsen of the University of Minnesota measured corona currents from the array atop the 1200 foot tower and the maximum value he recorded was of the order of 300μA under high field conditions. Perhaps the Telluric currents were there at that time, which would indicate that the maximum corona current should have been of the order of 450μA; a figure again in keeping with the values expected for a tower of this height.

The dissipation array was removed from the tower during the summer of 1975 and replaced by a 10 foot 1 inch copper lightning rod with a sharp point. The rod was well insulated from the tower with teflon, and corona current was measured by monitoring the voltage across a 10 or 100 ohm resistor in the line between the copper point and the well ground. A typical record of corona current, optical detector data and electromagnetic lightning flash data is shown in Figure 41. During stormy conditions the single point current often reached values of several hundred μA and the largest recorded was 720 μA. This value is considerably more than the maximum monitored

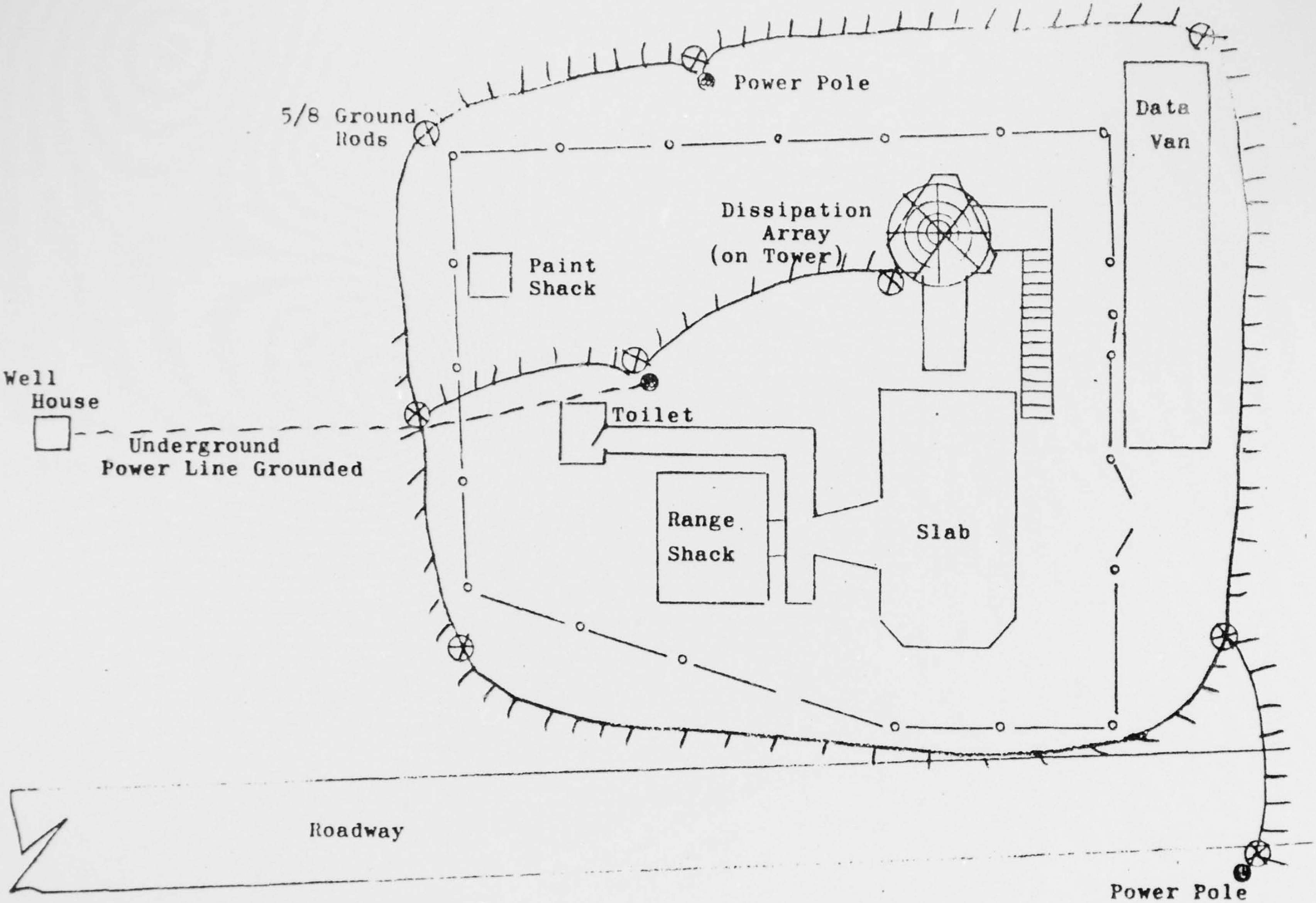

FIGURE 40. Improved grounding at site C9 during array installation

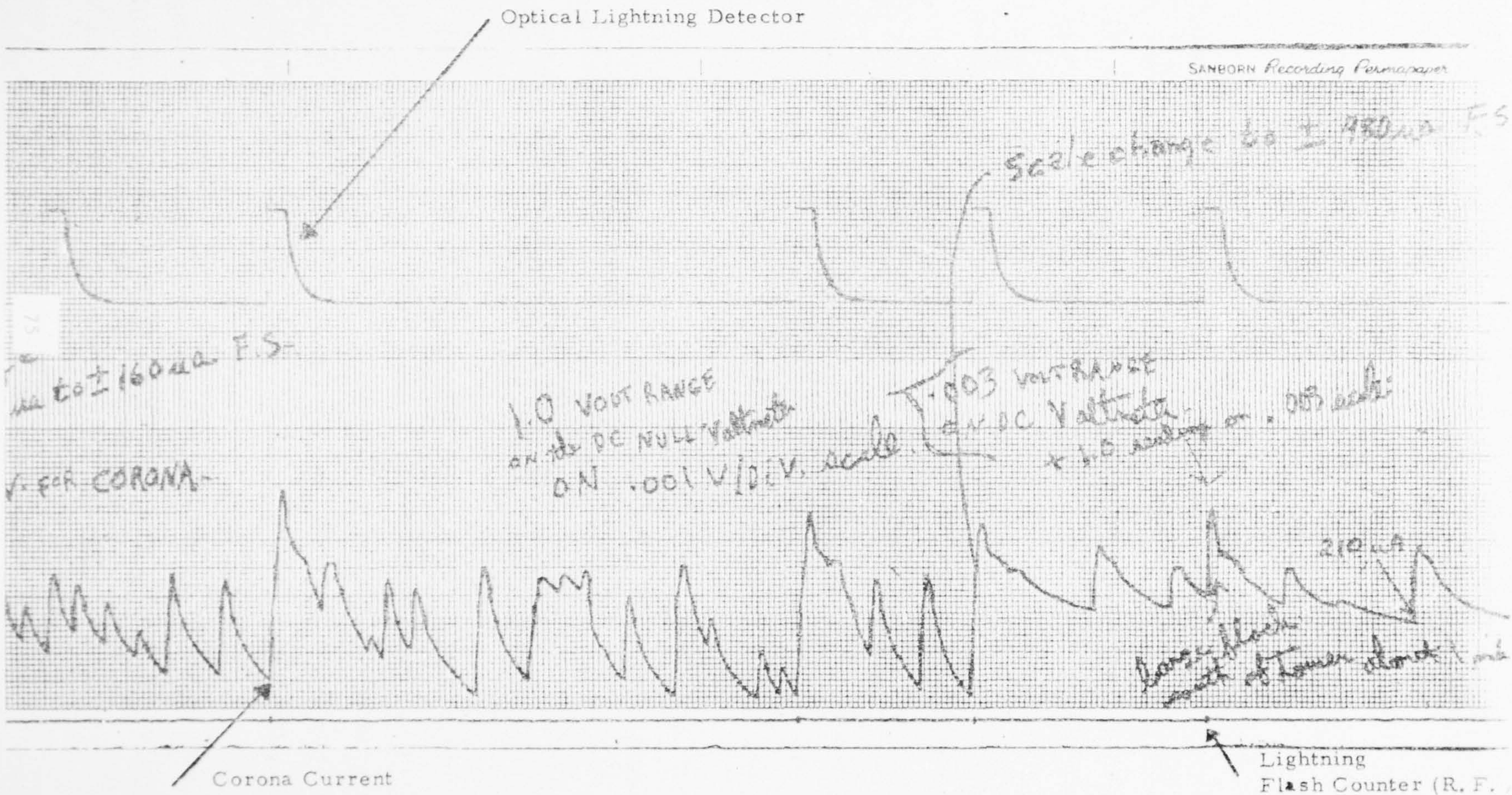

Figure 41. Corona Current Measurements from Single Point at 1200 ft. at C9, Eglin A. F. B.

by Prof. Olsen from the array which, in turn was more than that monitored by u[illegible]m the array. Values of array corona current were obviously hampered by Telluric currents in the grounding circuit, but at no time were any steady values recorded which approached the values in excess of 150 mA.[16]

It is interesting to note that the line between the resistor at the base of the tower and the corona recording device was occasionally subject to very short lived high currents which gave rise to heat bubbles in the wire; a feature one would expect from lightning currents passing down the tower. A further point of interest relates to the value of the resistance in the line between the corona point and ground. With a resistance of 10^6 ohms in the line and with $100 \mu A$ one would only lose 100 volts. The high electric field on top of the tower is enormous compared to this value and so grounding should not effect the corona current in any way.

The conclusions from this data are that the single point emits more corona than the multiple point array and that lightning is still striking the tower, but that it mainly passes harmlessly to ground.

7.4.2 Magnetic Link Measurements

Magnetic link data gave indications of lightning strikes to the tower on five occasions. Three of these were when the array was on top of the tower and two when the lightning rod was on top. The measurement technique is discussed in Section 7.2.

It was pointed out earlier that with the array on the tower there was no possible position of the magnetic links that would give unique current measurements, but they would only give an indication of the strike and a first order estimate of the current. The links at the top of the tower were attached to the array wire and were thus in excess of three feet from the main vertical tower structure. If lightning did strike the array the current would no doubt pass primarily down the 3 outer supports and little would be recorded on the links. At the base of the tower the links were fastened around the array wire and a main structure post and were

directed to the outside of the structure.

If lightning were to strike the tower or the guys it would probably pass most of its current to the center of the structure and not down the guy, primarily because of the much lower resistance to ground at the base of the tower.

The first three strikes to the tower in June and July 1975 measured currents in excess of 19000, 19000 and 37000 A at the base of the tower, but the first two strikes gave no indication of a strike some three feet below the array, whereas the third strike did. This could imply that lightning hit the uppermost guy wires, which pass to the tower some distance below the links, or that the position of the links and the low current was such that the strike was not recorded. Unfortunately the video photographs do not correlate with magnetic link data due to staffing problems and equipment failures.

A strike to the lightning rod in September 1975 passed down the magnetic link arm conductor which showed values in excess of 48000 A, and a second strike to the rod that month indicated values in excess of 25000 A. Like the other three strikes no damage was reported at these times to the tower electronic equipment. This data, therefore, upholds our suggestions that if the tower ground is intact to the well then no damage will result.

Examination of the array by USAF contractors in September 1975 showed definite evidence of lightning strikes and arcing between the array bolts and the tower.

7.4.3 Video Photography

While it may be possible to argue against recorded lightning strikes to the tower that are detected by electronic and magnetic means, photographs of such strikes are undeniable proof.

Unfortunately during the summer months the video equipment was only turned on for 17 occasions at the forestry tower and 10 occasions at the trailer over a 130 day period when storms were prevelant for over 40 of

these days. It has been suggested by Pierce [19 & 20] that there should be over 40 strikes to the tower during the year and so the chances were good that the video tapes would contain photographs of lightning to the tower.

Lightning strikes to the tower were photographed during the time period when the dissipation array was mounted on top. Coincidentally, no more video records of strikes to the tower were obtained, after the array had been replaced by a lightning rod. Figures 42a and b show two strikes to the tower as observed from the forestry tower on 1 May and 8 June 1975. The bright dot in the center of the picture is a fault on the silicon diode tube. Heavy rain was falling at these times, but later in the record the strike point was identified as the tower top. Further photographs of lightning to the 1200 foot tower array taken from the trailer are shown in Figures 43 a-c. These occurred in May 1975 within a few seconds of one another and there is no doubt that the strike was to the array at the top of the tower. Two minutes later the tape recorder was damaged by a large surge in the remote control line, which ran from the base of the tower, probably indicating another strike. Figure 43c shows much blooming but indicates an upward going leader as a horizontal branch to the west is shown, whereas two frames later when the camera blooming stops it is evident that the main strike is vertical.

On 16 May 1976, an interesting event occurred on 3 consecutive video frames viewed from the trailer. At the time of a lightning stroke to ground some distance beyond the tower, a spark of maybe 100-200 feet was seen to leave the array. This spark did not meet a downward leader and did not progress to become an upward leader.

These video results show categorically that lightning struck the array a number of times. This data, along with the magnetic link data, showed that the tower was struck ten times during the brief recording period, indicating the same strike frequency as Pierce's number of some forty times per year. During all these strikes to the tower no damage to the site electronic equipment resulted because the ground line was intact and had low resistance.

On September 23, 1975 the eye of hurricane Eloise passed close to the

1200 foot tower. The wind strengths were too severe for the structure and the tower blew down, thereby ending all further research at this site.

Figure 42a.

Figure 42b.

Lightning striking an array on top of the 1200 ft tower as viewed from the forestry tower

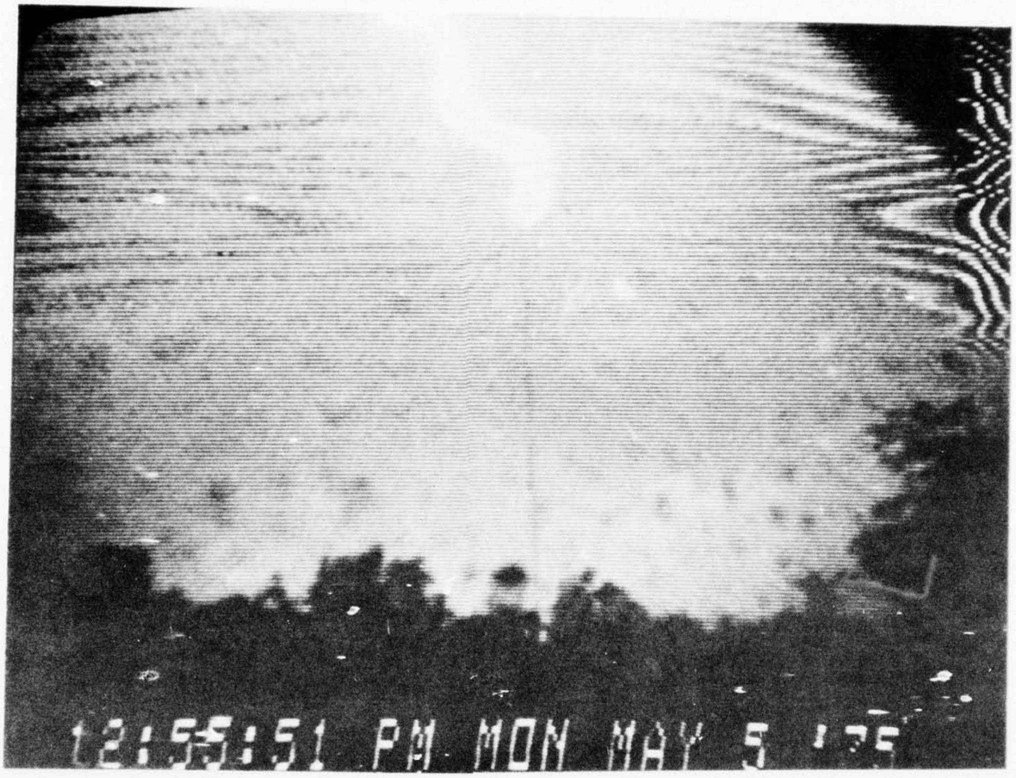

Figure 43 a.

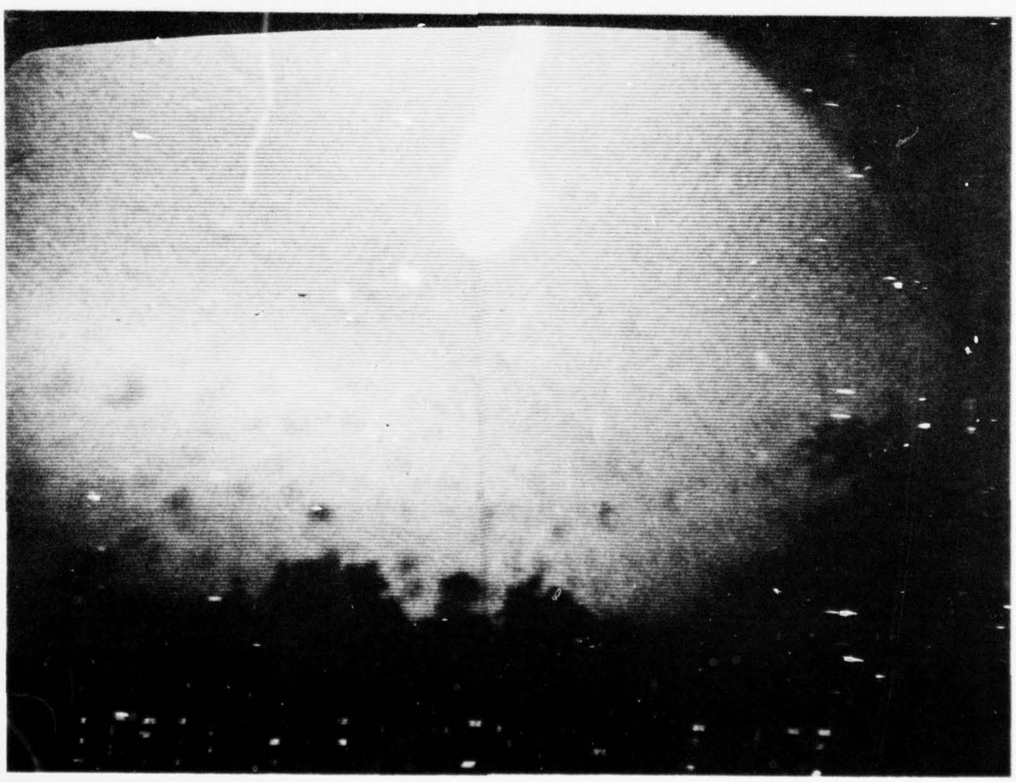

Figure 43 b.

Lightning striking the dissipation array atop the 1200 foot tower twice in two minutes

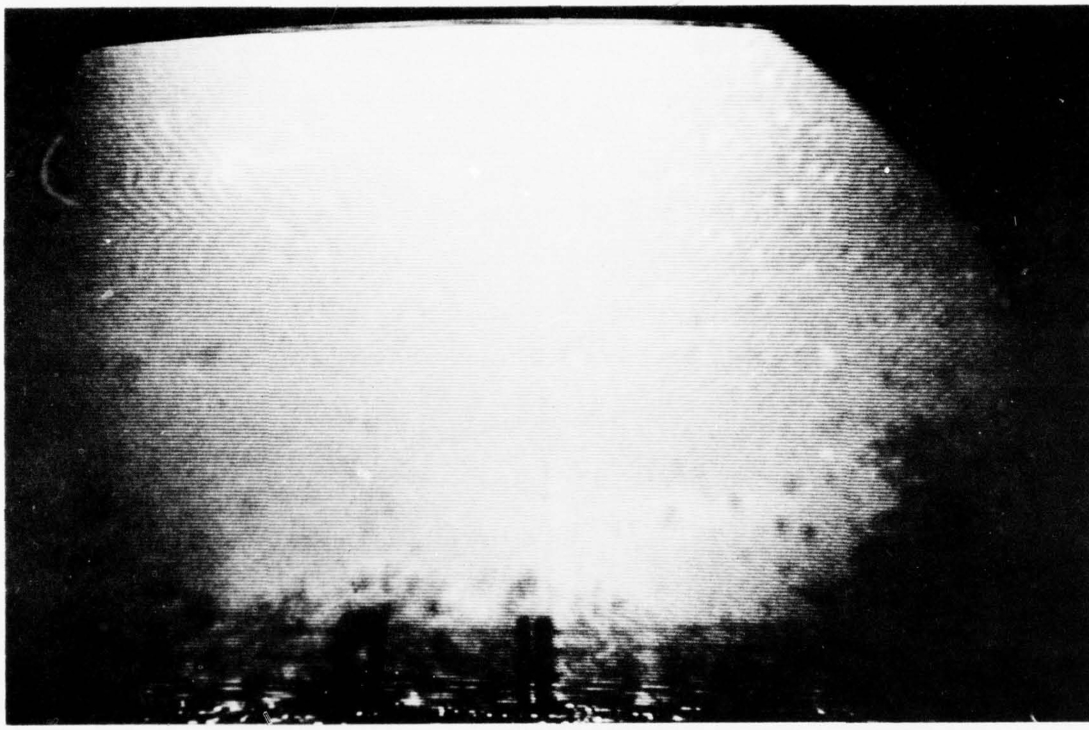

Figure 43c.

An upward-going leader from the dissipation array atop the 1200 foot tower

8.0 INVESTIGATIONS AT THE USCG JUPITER LORAN FACILITY

The U. S. Coast Guard Loran C transmitter Jupiter, Florida uses a 625 foot antenna tower which rests on an insulated base. The tower is connected to ground through the secondary coil of the final transmitter transformer. The ground plane is comprised of many radial wires a few hundred feet long radiating from the tower base. The purpose of this study was to review the problem of lightning protection and to examine any possible improvements.

The base of the tower is shown in Figure 44a from which one can see the insulator, spark gaps and the tower lights' isolation transformer. The antenna lead is seen entering the transmitter building and the return line is seen going to ground.

Magnetic links were placed on the transmitter wire between tower and building in order to measure lightning currents passing to the transformer. Figure 44b shows these links being put in place and also shows the spark gaps across one of the air-cored isolation transformers.

The possibility of protecting the tower or the associated electronic equipment against lightning damage is rather remote. The major problem is not being able to ground the tower directly because it is the transmitting antenna. It has been suggested that dissipation arrays be mounted on the tower which is effectively at DC ground potential and that the ensuing corona current would dissipate the storm. The results and conclusions in the preceeding chapters however cast considerable doubt on the feasibility of this approach, as any lightning protection system must be adequately grounded.

Basically we must either prevent lightning from striking the tower, or, if it does, we must attempt to protect the transformer from receiving a large portion of the current.

Protecting the tower from lightning strikes is considered by many scientists to be an impossible task, but one or two ideas have been put forward that contain merit.

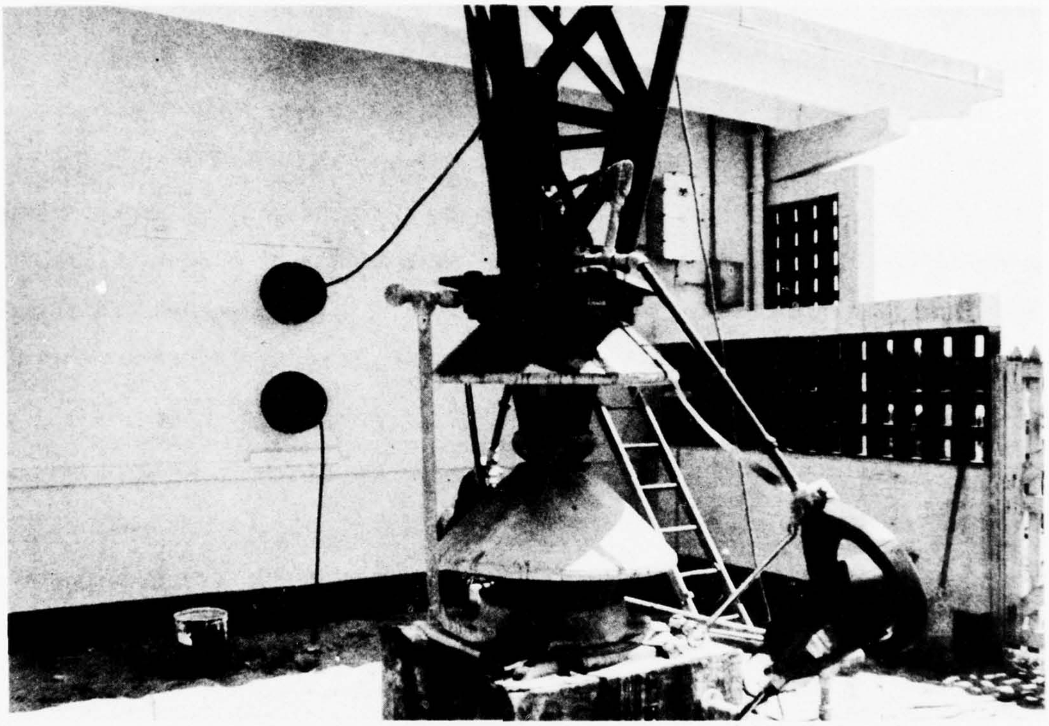

Figure 44a. The base of the USCG, Loran C antenna at Jupiter, Florida showing the insulated base, spark gaps and transmitter leads

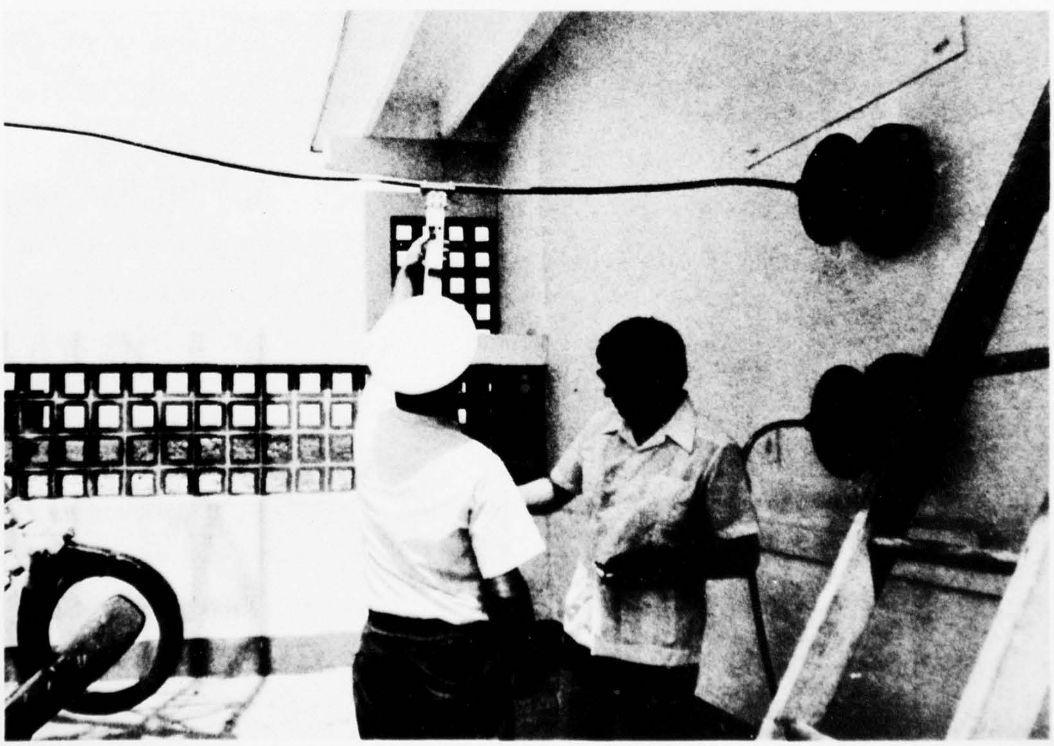

Figure 44b. Magnetic links being fitted to the transmitter feed cable at the base of the 625 foot Loran C antenna

As indicated in Section 3.2, blunt points tend to go into corona over a much larger volume than sharp points and therefore one can assume that blunt points will attract lightning by sending out a longer spark to meet the downward leader. Similarly one may assume that sharp points tend to protect themselves. This latter hypothesis has been put forward by scientists from New Mexico Institute of Mining and Technology. It has also been theorized that if uniform corona can be emitted from around a structure then the glow to arc discharge region will possibly be suppressed leading to a reduction in the number of upward streamers, Golde[26].

In practice, however, it will be extremely difficult, if not impossible, to set up the right number of points at the right places such that no singular very high fields exist. If such a configuration can be achieved, it is unlikely to affect the normal downward leaders but may reduce the number of upward going leaders. As shown in Section 4.0,for a tower of this height the proportion of triggered to natural lightning is only about 1, implying an average 2 to 3 normal and 2 to 3 triggered strokes to the tower per year. On this basis it was decided to make some simple attempts to investigate the above hypothesis.

Silicon diode video cameras were used at two sites, one to photograph the incidence of lightning to the tower and nearby, and the other to photograph the region at the top of the tower to investigate the behavior of pointed and blunt objects placed at the top. As reported in Section 7.0, a long spark was seen to leave the array atop the 1200 foot tower during nearby lightning and the spark did not connect with a downward leader. With a predicted 6 strikes a year to the Loran tower and no doubt a similar number nearby, we believed the chances of seeing sparks were good.

The equipment was installed in late May 1975 and correctly adjusted and aligned by mid-June. Unfortunately the tower was hit by lightning on 18 June 1975 before the video filters had been correctly adjusted for close lightning. The strike caused blooming of the cameras and the resulting photograph is shown in Figure 45a. A typical more distant intra-cloud flash is shown in Figure 45b. No more strikes to the tower occurred during the whole thunder-

Figure 45a. A 37kA lightning strike to the 625 foot Loran C antenna causing excessive camera blooming

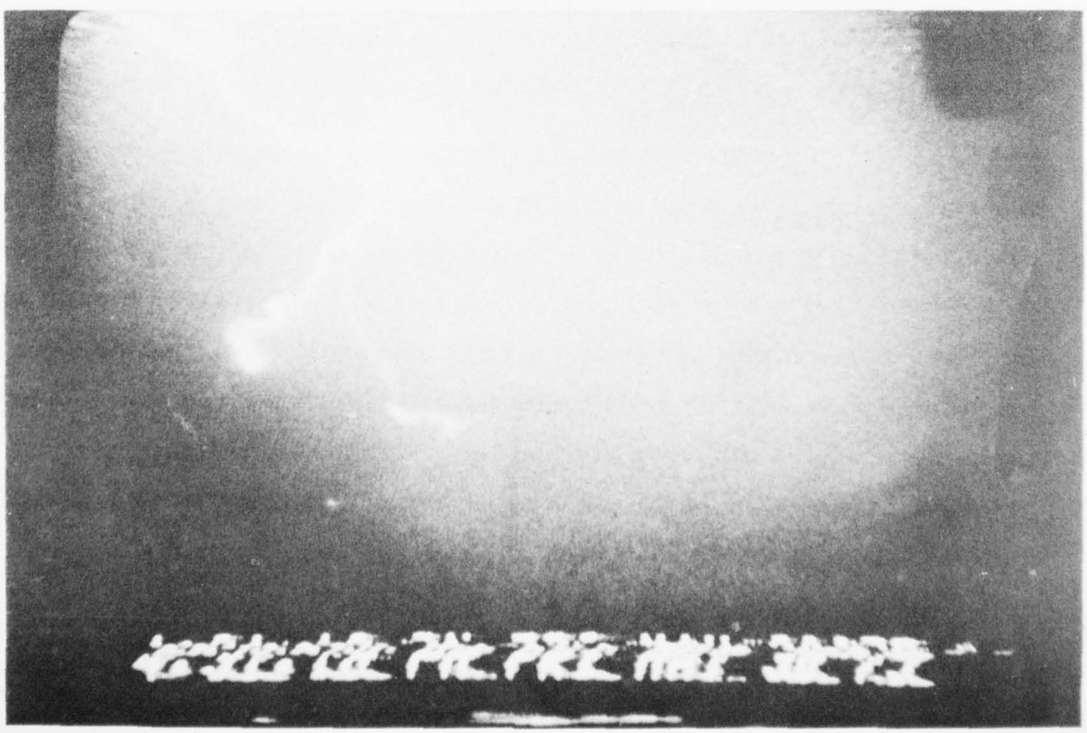

Figure 45b. Intra-cloud lightning above the Loran C antenna at Jupiter, Florida

storm season and after that occasion there were also very few close strikes.

The video signals were degraded due to the strong Loran transmissions but all the data was satisfactory. The electric field change was monitored and during the presence of close lightning an audible tone was recorded along with the video signal. This enabled us to perform a more accurate review of the tower top during such strikes.

A sharp point and a 12 inch smooth hemisphere were the two objects placed one at a time on top of the tower. Disappointingly for the experiment there were no more very close strikes and so no sparks were monitored. Only one strike to the tower therefore occurred during the summer thunderstorm season.

During the strike of 18 June 1975, 32kA were monitored passing into the secondary coil of the transmitting transformer. This strike contained only one return stroke as monitored on video and was probably upward going.

One may argue that modification of the tower top with multiple corona points in some hemispherical fashion may reduce the upward going leaders, but it is unlikely that all points could be contained in a "glow" condition thereby eliminating the spark. Downward leaders would also still strike the structure.

When lightning hits the tower, current can be anywhere from a few thousand to a few hundred thousand amperes. This current must pass to ground either by passing directly to ground through the output transformer, or by arcing across the ball gaps, or both. A 2-0 insulated copper wire is installed on the tower and connected at the top and bottom to the main structure. Should this wire be connected to an insulated lightning rod which is struck by lightning, there is a possibility that the current may be "shocked" into passing primarily to the base of the wire which could be connected to a ball gap. Much current will still arc to the tower and pass through the transformer, but the amount may be reduced.

There is not much improvement one can achieve if no connections can be made to ground for fear of interfering with the transmissions. If a choke could be made at the Loran frequency of 100 kHz and connected from ground to tower

base, a DC path to ground would exist for the lightning current and yet at 100 kHz the resistance to ground would be very high. This is the approach used by AM radio stations, but at those frequencies RF chokes are easily made. The only alternative left is to maintain the existing ball gaps with a clean and smooth surface and to adjust the gaps for minimum distance.

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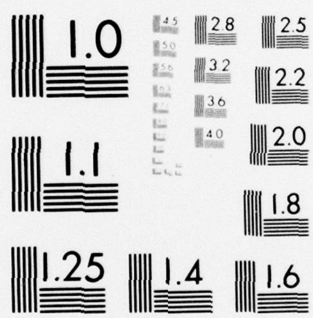

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9.0 CONCLUSIONS

This investigation covered the historical, theoretical, experimental aspects and previously published reports relating to the dissipation array principle of lightning protection and elimination. The overwhelming evidence implies that the arrays tested do no more protecting than a conventional lightning rod would do, and that the arrays do not eliminate lightning, as many strikes have been photographed and currents of 30-50 kA have been measured. The main findings of the investigation are as follows:

1. Historic data shows that single point corona current exceeds multiple point current. (Section 1)

2. Historic data shows that maximum currents from multipoint arrays elevated about a hundred feet are only a few tens of microamperes. (Section 1)

3. Corona discharge from beneath a thunder cell will not influence the cells' electrical charge. (Section 2)

4. The maximum current recorded from a large multipoint array at 100 feet under a severe storm was under 40μA. (Section 6)

5. Corona measurements from a single point at 50 feet always exceeded those from a dissipation array at the same height. (Section 6)

6. Corona current from natural sources such as a few trees will often exceed that of a dissipation array. (Section 2)

7. Corona current cannot provide a protective ion cloud for a large area and thus to prevent lightning already in motion from striking. If such a cloud existed it would be more dangerous than the initial lightning stroke. (Section 2, 3)

8. The dissipation arrays do not eliminate lightning. (Section 7)

9. Improvement of grounding systems, or introduction of RF chokes in the case of isolated antenna systems, and surge protection are the major causes in the reduction of lightning damage. (Sections 7, 8,)

10.0 RECOMMENDATIONS

As a result of this extensive and thorough investigation of multipoint lightning protection systems, it is evident that such systems cannot be recommended for use at FAA facilities because they offer no better protection than a conventional air terminal system. The expenses that would ensue from multipoint systems due to their structural size, and the safety hazards that have to be overcome can clearly be avoided. The FAA should continue to pursue a lightning protection program following conventional practice. It should include lightning conductor installations, as specified in the national lightning protection codes, and surge protection for sensitive electronic circuitry. This approach is economically the most feasible and provides adequate protection based on the statistical data of lightning and the results from theoretical investigations. In addition, it is suggested to keep in touch with the scientific community. The progress of investigations on sharp versus blunt points for the use as protective air terminals should be followed and possible new recommendations should be pursued.

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